STATE OF ALASKA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS

Tony Knowles, *Governor*

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A PRELIMINARY EVALUATION OF ALLUVIAL
DIAMOND DISCOVERIES IN PLACER GRAVELS OF
CROOKED CREEK, CIRCLE DISTRICT, ALASKA

by
R.B. Forbes, J.T. Kline, and A.H. Clough
In cooperation with the U.S. Bureau of Mines

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CONTENTS

	<u>Page</u>
Abstract.....	1
Acknowledgments.....	2
Introduction.....	2
The Crooked Creek diamond discoveries.....	5
The Regan diamond.....	5
The Warren diamond.....	7
The Manuel diamond.....	7
Implications of the Crooked Creek diamond discoveries.....	7
Primary sources and transport history.....	7
Prospecting targets and methods.....	7
Lessons learned from diamond exploration in Siberia.....	9
Gold vs. diamond recovery in placer-mining operations.....	9
Alluvial diamond recovery plants.....	9
Regional and local geology.....	10
Crooked Creek alluvial history.....	10
Stratigraphy of the alluvial deposits.....	12
Upper (gray) gravel.....	12
Lower (yellow) gravel.....	12
Reconnaissance sampling of the Crooked Creek gravels.....	15
Placer-gold deposits.....	15
Characteristics and distribution of Crooked Creek gold.....	16
Placer-gravel and concentrate evaluation.....	16
Primary objectives.....	16
Background.....	16
Crooked Creek mining methods and sample recovery.....	17
Description of samples.....	19
Pan concentrates (1985).....	19
Sluice concentrates (1985).....	19
Sluice tailings (1985).....	19
'Pan American' jig concentrates (1985).....	19
Hydraulic jig concentrates (1986).....	19
Sample analysis.....	20
Grease-table tests.....	20
Grease-table design and operation.....	21
X-ray screening of selected jig concentrates.....	21
Laboratory studies of concentrates.....	21
Sample preparation and examination.....	21
Apparent absence of microdiamonds and indicator minerals.....	22
Conclusions.....	22
Selected references.....	26

FIGURES

Figure 1. Map of Alaska showing the location of the Goodnews Bay and Crooked Creek diamond discoveries.....	3
2. Location map (Circle C-2 and C-3 Quadrangles) showing the discovery sites of the Regan, Warren, and Manuel alluvial diamonds in gravels of the Crooked Creek district, Alaska.....	4

FIGURES (con.)

	<u>Page</u>
3. Photographs of Al Clough, U.S. Bureau of Mines, a) applying petroleum jelly to the grease table prior to test runs and b) inspecting concentrate as it descends the steps of the table during a field test.....	6
4. Enlarged photographs of the Crooked Creek diamonds: a) Regan diamond, 0.33 kt; b) Warren diamond, 1.4 kt; and c) Manuel diamond, 0.8 kt.....	8
5. Map showing the major tectonic features of the Circle Quadrangle and the location of the Crooked Creek diamond discoveries.....	11
6. Diagrammatic cross-section of the Crooked Creek alluvial deposits.....	13
7. Diagrammatic section of alluvial deposits exposed in a placer-mining cut on one Warren claim on Crooked Creek, summer 1985.....	14
8. Photographs of Warren sluice plant in operation on Crooked Creek showing a) the delivery of gravel with the front-end loader and b) the grade and design of the sluice boxes.....	18
9. Tectonostratigraphic terrane map of western North America showing the edge of the North American plate and the locations of diamond-bearing kimberlites and recent Alaskan placer-diamond discoveries.....	24
10. Simplified lithostratigraphic terrane map of the Yukon-Alaska International Boundary region showing the interrelationship of the North American plate and adjacent Alaskan lithostratigraphic terranes and the location of tectonic and geologic features discussed in the text.....	25

TABLE

Table 1. Information on concentrates obtained and evaluated in 1985-86.....	20
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A PRELIMINARY EVALUATION OF ALLUVIAL DIAMOND DISCOVERIES IN PLACER
GRAVELS OF CROOKED CREEK, CIRCLE MINING DISTRICT, ALASKA

By
R.B. Forbes,¹ J.T. Kline,² and A.H. Clough³

ABSTRACT

Three alluvial diamonds have been discovered on Crooked Creek, near Central, Alaska, since large-scale placer gold mining began in 1980. The stones, which range in weight from 0.3 to 1.4 kt, were accidental finds recovered during sluice-box clean-ups. The diamonds display percussion marks, fractures, and rounded interfacial edges that suggest a long and possibly complicated alluvial history.

Most placer gold won from Crooked Creek gravels is recovered from the upper (gray) gravel that overlies a lower, highly weathered and clay-rich (yellow) gravel of unknown (>90 ft) thickness. Both gravel units contain clasts that were apparently derived from the south, in the Yukon-Tanana Uplands. We do not know the depositional age of this lower and more highly weathered gravel, which could be as old as Tertiary or as young as Pleistocene. When frozen, the ice content of the lower unit is greater than that of the upper gravel, and it is considered and treated as bedrock by most miners.

The lower gravel is seldom mined due to low gold and high clay content. However, some of this material finds its way into the sluice plants when pockets of high-grade gray gravel that extend into the lower unit are mined with the adjacent lower gravels. Both types of gravel were run through the sluice plants prior to the discovery of each Crooked Creek diamond, and there is a fair probability that the stones are being recovered from the lower gravel.

Although pan-, sluice-, and jig-concentrate samples---and tailings samples---were examined for both kimberlite indicator minerals and diamonds, none were found during this study. These findings coincide with those of corporate geologists who also reported negative results following their studies of various concentrates from the Crooked Creek gravels.

Sluice plants designed for gold recovery are completely unsuited to alluvial diamond mining and exploration due to the relatively high specific gravity of gold (15-19) vs. diamond and kimberlite indicator minerals (3.2-3.5). An unknown number of diamonds have probably been discharged with the tailings during placer-mining operations on Crooked Creek over the last few years.

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Primary sources for the diamonds in the surrounding region have not been identified, and there are no known occurrences such as kimberlites or lamproites. However, diamond-bearing diatremes are very small targets, and the reconnaissance level of geologic knowledge in most possible source areas does not permit hasty conclusions. If the Crooked Creek diamonds are of multicyclic origin (for example, derived from the reworking of older placer deposits), they may have been derived from paleoplacers in Tertiary rocks that occur in nearby areas.

The tectonic framework of the Porcupine River region north of the Yukon River most favors the occurrence of kimberlitic rocks, followed by the Yukon-Tanana Uplands and the Crazy Mountains, respectively.

The Crooked Creek diamond discoveries merit a properly equipped exploration and evaluation program supported by specialized equipment designed for diamond recovery and exploration, including jigs, heavy-media separation plants, and grease tables. If additional diamonds are found, an X-ray sorter will accelerate the evaluation.

A regional exploration program for possible diamond-bearing diatremes should follow the 'Siberian Model,' with priority attention given to a systematic search for 'sputnik' or indicator minerals in stream sediments and soils in appropriate drainages, followed by surface and airborne geophysical surveys for target definition.

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We are indebted to the mining families of Crooked Creek and Central, Alaska, who have made this study and report possible through their help, cooperation, and warm hospitality. We are particularly indebted to Frank and Mary Warren, Jim Regan, the Gelvin family, Don Mays, and Paul Manuel.

We also extend our thanks to Howard Coopersmith and Cominco American, Inc., for the opportunity to learn and benefit from the use of the Cominco diamond-recovery facility in Fort Collins, Colorado. Robert Cacy graciously allowed us to use his jig plant on Portage Creek for experimental recovery runs and Jim Madonna (Alaskan Prospectors and Geologists) provided a portable water pump that was used to evaluate the hydraulic jig. We also benefitted from helpful suggestions by Florence Weber and Warren Yeend, Alaska Branch, U.S. Geological Survey, and W.D. Hausel, Wyoming Geological Survey.

INTRODUCTION

In the summer of 1982, Jim Regan reported the discovery of a small diamond that was recovered during placer-mining operations on Crooked Creek, near Central, Alaska ('Fairbanks Daily News Miner,' December 11, 1984). Although a subsequent examination of the Regan properties by associates of the DeBeers Group failed to locate additional diamonds or a possible bedrock source in the surrounding area, two diamond discoveries on the same creek in 1984 and 1986 reinforced the validity of the first find and generated much interest in the Circle Mining District as a possible diamond province (figs. 1, 2).

Figure 1. Map of Alaska showing the location of the Goodnews Bay and Crooked Creek diamond discoveries.

Figure 2. Location map (Circle C-2 and C-3 Quadrangles) showing the discovery sites of the Regan (1), Warren (2), and Manuel (3) alluvial diamonds in gravels of the Crooked Creek district, Alaska.

To our knowledge, the Crooked Creek stones are the only documented diamond discoveries in Alaska, with the exception of two microdiamonds obtained from the insoluble residue of dissolved platinum alloy nuggets (Mertie, 1976) and a 'single tiny diamond' recovered from a core sample from bottom sediments in Goodnews Bay (fig. 1; Hoare and Cobb, 1977).

We visited the Crooked Creek discovery sites in June and September 1985 and August 1986 to document the circumstances surrounding the discovery of the diamonds. Of particular interest was the placer-mining and clean-up techniques used at the time of the discoveries and the lithology and mineralogy of the gold-bearing gravels that produced the diamonds.

After a brief field reconnaissance and discussions with the Crooked Creek placer-mining community, the field program was expanded to include studies of the alluvial gravels and surficial geology of adjacent areas and a detailed examination of heavy-mineral concentrates from selected zones in the placer gravels. Heavy-mineral studies included examinations of clean-up concentrates obtained from the Regan and Warren mining operations. Panned concentrates and other concentrates from large-volume gravel samples (jig runs) were examined in an attempt to recover minerals in the diamond and indicator-mineral density range. A small grease table was taken to the field to extract diamonds from the various concentrates (fig. 3a,b). Concentrates and gravel samples were returned to the laboratory, where mineral concentrates obtained from heavy-liquid separations were microscopically examined for indicator minerals and microdiamonds.

This report summarizes the findings of reconnaissance field and laboratory studies conducted by the Alaska Division of Geological and Geophysical Surveys (DGGs) and the U.S. Bureau of Mines in 1985 and 1986 on the new diamond discoveries; a summary of the origin, lithology and mineralogy of the Crooked Creek alluvial deposits is also included. Geologic factors conducive to the possible occurrence of diamond-bearing kimberlitic or lamproitic source rocks in adjacent areas are discussed.

THE CROOKED CREEK DIAMOND DISCOVERIES

The Regan Diamond

The Regan diamond was discovered by Don Lasley during clean-up operations at Jim Regan's gold placer-mining operations on the Diamond No. 1 claim on Crooked Creek (fig. 2). The stone is a clear, rounded octahedron that weighs about 1/3 kt (fig. 4a). The diamond was first shown to John F.M. Sims, former Director of the Alaska Department of Commerce and Economic Development, Office of Mineral Development. Sims forwarded the stone to a DeBeers subsidiary, who confirmed that the stone was a diamond.

Subsequently, two DeBeers associates visited the Regan claims and the surrounding area, but examinations of placer concentrates and reconnaissance studies of local alluvial and bedrock geology failed to produce additional diamonds, indicator minerals, or evidence of nearby kimberlite or lamproite diatremes.

a

b

Figure 3. Al Clough, U.S. Bureau of Mines, a) applying petroleum jelly to the grease table prior to test runs and b) inspecting concentrate as it descends the steps of the table during a field test.

The Warren Diamond

In the summer of 1984, Mary Warren discovered a 1.4 kt diamond during secondary clean-up work on concentrates from the Warren placer-mining operations on Crooked Creek, about 2 1/2 mi downstream from the Regan claims, where the first stone was discovered. The Warrens were initially unsure of the nature of the stone, but Don Stein, former State Assayer, saw the stone during a visit to Central and suspected that it was a diamond. At Stein's urging, the stone was examined and confirmed to be a diamond in DGGs laboratories; final confirmation was obtained from the Gemological Institute of America.

The Warren diamond is a yellow-white stone with the form of an apparent deformed or pseudo-dodecahedron (Robinson, 1973). Numerous small, crescentic indentations identified on the crystal faces under high magnification are probably percussion marks resulting from an extensive and perhaps complicated alluvial history (fig. 4b).

The Manuel Diamond

In July 1986, Paul Manuel recovered a third diamond from the Crooked Creek gravels about 1,500 ft downstream from the Warren discovery. The diamond weighs 0.83 kt, is light yellow, and has the crystal form of a twinned dodecahedron (fig. 4c). Although the Warren diamond emits a green fluorescence under long-wave ultraviolet light, the Manuel stone fluoresces light blue. Similar to the Warren stone, the crystal faces of the Manuel diamond are covered with very small percussion marks resulting from transport in the alluvial environment. The diamond was discovered during clean-up of riffle sets in the headward section of a sluice box.

IMPLICATIONS OF THE CROOKED CREEK DIAMOND DISCOVERIES

Primary Sources and Transport History

The discovery of three alluvial diamonds in gravels from the same creek deserves serious attention from geologists and explorationists. However, the search for primary sources for the Crooked Creek diamonds may be long and complicated because no primary source rocks (kimberlitic or lamproitic diatremes) have been identified in the area dissected by the Crooked Creek drainage net. Furthermore, worldwide experience has shown that alluvial diamonds may have multicyclic histories that include erosion and transport from pre-existing 'fossil' placers or secondary sedimentary host rocks.

Prospecting Targets and Methods

Typical diamond-bearing diatremes (pipes) are very small (approximately 300 to 3,000 ft diam). This size constraint, along with the presence of vegetation and standing water at lower elevations and frost-rived block fields and frost-disturbed surficial deposits above timberline, compromise the effectiveness of airborne geophysical and remote-sensing prospecting techniques in northeastern Alaska.

A

B

C

Figure 4. Enlarged photographs of the Crooked Creek diamonds: a) Regan diamond, 0.33 kt; b) Warren diamond, 1.4 kt; and c) Manuel diamond, 0.8 kt. Photograph of the Regan diamond courtesy of Jim Regan; photographs of the Warren and Manuel diamonds by R.B. Forbes.

Lessons Learned from Diamond Exploration in Siberia

Russian geologists successfully solved similar problems in their search for diamond-bearing kimberlite diatremes in the tundra-taiga environment of eastern Siberia, where alluvial diamonds were also discovered in placer gold-mining operations. Source diatremes were eventually located through a systematic, regional, heavy-mineral survey of stream sediments and soils using pyrope garnet, chrome diopside, and magnesian ilmenite, which appear to be ubiquitous mineral phases (indicator or 'sputnik' minerals) in diamond-bearing kimberlites. After larger target areas were defined by high concentrations of indicator minerals in residual soils and stream sediments, surface and low-level airborne magnetometer surveys successfully located and defined the concealed diatremes.

More recently, diamond exploration parameters have been complicated by the discovery of economically important diamond deposits in West Australian diatremes composed of lamproite rather than kimberlite. Many lamproites do not produce the typical diagnostic indicator minerals that characterize diamond-bearing kimberlites.

Many factors, including the lessons learned by Russian geologists during the analogous exploration program in Siberia, are being considered in our evaluation of the Crooked Creek diamond discoveries. In the case of accidental alluvial diamond discoveries, the primary source (or sources) may never be found. Many alluvial and accidental diamond finds have not been traced to a source diatreme, and source diatremes for mineable alluvial diamond deposits in Brazil and India have not been located.

Gold (1984) cautioned that the presence of microdiamonds in alluvial deposits does not necessarily indicate a primary source, because some microdiamonds may be of extra-terrestrial origin.

Gold vs. Diamond Recovery in Placer-mining Operations

Sluice and wash plants used for gold recovery in typical Alaskan placer operations are not satisfactory for diamond recovery and prospect evaluation because of the relatively low specific gravity of the diamond (3.5) vs. gold (15-19) and many other heavy minerals.

Although alluvial diamond deposits can be extremely rich (for example, 500 kt/ton, according to Orlov, 1977), most diamond-bearing gravels contain diamonds in much lower concentrations. Realistic examples of rich, large-volume alluvial diamond deposits are those adjacent to the Argyle AK1 diatreme in western Australia, which average about 3.5 kt/ton (about 1.5 yd³). Considering the relative richness and mineability of these deposits, it is clear that a reliable placer evaluation program will involve sampling and processing large-tonnage samples (hundreds or thousands of cubic yards) to obtain a valid assessment of diamond concentration and grade.

Alluvial Diamond Recovery Plants

The cleaning and sizing capabilities of wash plants offer an efficient

and quick solution to discarding oversize material ($>1/2$ to $3/8$ in.) and cleaning and preparing bank-run material for processing by jigs and heavy-media plants. If grease tables are used for the final extraction of diamonds from concentrates, it may be necessary to 'prep' the concentrates with an additional abrasive wash to insure that the diamonds, if present, are free of surface coatings that may cause some diamonds to pass the grease table.

Various jigs are commercially available that are satisfactory for the recovery of heavy-mineral concentrates from diamond-bearing gravels. Another option is the use of so-called 'heavy-media' plants that have been successfully used in diamond exploration in western Australia. These plants mix clean, sized material with a slurry of ferrosilicon prior to circulation in a cyclone. The heavy fraction sinks through the ferrosilicon medium, which is then magnetically recovered and returned to the circuit. Concentrates from either type of plant (or both) can then be passed over a grease table or through an X-ray sorter.

Another option for very small-scale evaluations is heavy-media separation using methylene iodide (sp gr = 3.2), visual identification with a binocular microscope, and hand picking of indicator minerals and diamonds.

REGIONAL AND LOCAL GEOLOGY

The segment of Crooked Creek that produced the three diamonds lies within the Tintina fault zone, which is bounded on the northeast by the Preacher Creek strand and on the southwest by the Hot Springs strand of the fault (fig. 5; Foster and others, 1983). In this area, the fault zone is in part a Tertiary basin filled with an unknown thickness of continental clastic rocks that range in age from Miocene to Pliocene (Weber and Foster, 1982). These deposits are overlain by 5 to 100 ft of Quaternary flood-plain, terrace, and fan gravels. Potential source areas for the Tertiary basin fill include the Crazy Mountains to the north and the Yukon-Tanana Upland to the south. Bedrock in the Crazy Mountains consists of late Proterozoic through late Paleozoic sedimentary, metasedimentary, and metavolcanic rocks. Dominant rock types recognized in the Yukon-Tanana Upland south of the Hot Springs fault include greenschist- and amphibolite-facies metamorphic rocks that are intruded in some areas by granitic plutons of Late Cretaceous age (Foster and others, 1983). A few mafic and ultramafic bodies also occur along the trace of the Hot Springs fault in association with metamorphic rocks of the Yukon-Tanana basement complex.

Crooked Creek Alluvial History

Crooked Creek, a tributary of Birch Creek, heads in the Yukon-Tanana Upland and drains northeast through a graben valley (successor basin?) that is bounded by the Preacher and Hot Springs strands of the Tintina fault. The morphology of the Crooked Creek drainage basin documents a complex history of changes in regional and local base levels and channel migration within the fault zone. These changes are in part related to uplift of the Yukon-Tanana Upland relative to the block bounded by the two strands of the Tintina fault. Significant changes in stream regimen and local base level resulted in

Figure 5. Map showing the major tectonic features of the Circle Quadrangle and the location of the Crooked Creek diamond discoveries (modified from Foster and others, 1983).

multiple cycles of aggradation, rejuvenation, and downcutting. The present stream is incised approximately 100 ft into fan gravels that were deposited in the subsiding graben valley. The width of the incised fan segment is between 1,000 and 3,000 ft.

Stratigraphy of the Alluvial Deposits

Alluvial stratigraphy exposed in mining cuts along Crooked Creek consists of a discontinuous upper unit of 3 to 5 ft of dark-gray, laminated, fluvial

(overbank) organic silt and minor sand underlain by 5 to 15 ft of Holocene or late Pleistocene gray to brown, cobble to small-boulder gravel with some sand (henceforth called the 'upper or gray gravel'), which in turn overlies an unknown thickness of highly weathered yellow to orange cobble-boulder gravel with a sandy clay matrix (henceforth called the 'lower or yellow gravel'). In some placer cuts, another alluvial gravel unit that is somewhat older than the upper (gray) gravel apparently forms ice-wedge casts that penetrate the lower gravel. In some cases, this gravel fill may be genetically related to the marginal fan into which the channel of modern Crooked Creek is incised (figs. 6, 7).

Upper (Gray) Gravel

The upper gravel is dominated by clasts of quartz-mica schist, quartzite, and subordinate granitic rocks of the Yukon-Tanana crystalline terrane. Apparently, most placer gold mined from Crooked Creek alluvial deposits is located in the upper gravel.

Lower (Yellow) Gravel

Lithologies of pebbles, cobbles, and boulders from the lower gravel indicate that the most probable source area is the Yukon-Tanana Upland. Pervasive weathering and alteration have decomposed most feldspathic and ferromagnesian components of the clasts, and the unit is characterized by a high clay content and a yellow to orange-red pigmentation derived from secondary hydrous iron oxides. Most granitic clasts are decomposed to friable aggregates of gruss and clay.

In some exposures, the upper part of the lower gravel looks very much like weathered glacial till, but to our knowledge no alpine glaciers from the Yukon-Tanana Upland reached the Yukon lowlands during the Pleistocene glacial maxima. Poor fluvial sorting of the original deposits, complicated by periglacial processes (permafrost, solifluction, and extensive weathering or alteration) may be responsible for the till-like aspects of the lower gravel.

The depth and uniformity of weathering in the lower gravel are difficult to evaluate because no exposures of more than a few feet were observed. Local miners who use churn drills to test the lower gravel report that it is >90 ft thick. To our knowledge, bedrock has not been reached in any drill test in this distinctive gravel unit on lower Crooked Creek downstream from the Hot Springs fault. The lower (yellow) gravel has not been reported from localities south of the fault, which implies that any part of the yellow gravel that may have extended south of the fault has been removed by erosion that accompanied uplift of the Yukon-Tanana block. Results from drill tests indicate that the gravel is uniformly clay rich and weathered at depth.

Fresh cuts made by Frank Warren in the upper few feet of the lower gravel reveal possible ice-wedge casts. Placer miners generally remove and process the upper auriferous gravel down to the contact with the lower gravel, which the local miners commonly identify as 'false bedrock' or 'the Tertiary.' The exhumed contact frequently exhibits anastomosing polygonal patterns that

Figure 6. Diagrammatic cross-section of the Crooked Creek alluvial deposits (based on geological data from mining cuts on the Regan and Warren claims).

Figure 7. Diagrammatic section of alluvial deposits exposed in placer-mining cut on one Warren claim on Crooked Creek, summer 1985.

appear to be relict ice-wedge polygons that were subsequently filled by younger gravels. These large pockets of the upper gravel seem to form near intersections of presumed ice-wedge casts. Pockets of upper gravel inset into the lower are usually 5 to 20 ft across and 3 to 8 ft deep; they are selectively mined because they commonly contain relatively high gold values.

Approximately 2,000 ft upstream from the Warren claims, a fairly abrupt change occurs in the color and overall uniformity of iron staining, and there is an apparent increase in the intensity of weathering and alteration. Remnants of highly weathered and disintegrated schistose pebbles, cobbles, and boulders are dominant. The lower gravel unit may be tilted and dip to the north, causing gravels upstream from the Warren claims to be stratigraphically deeper in the section and thus older. Alternatively, the more intensely weathered gravels upstream may be closer to a source of alteration associated with fluids emanating from the Hot Springs fault. Mining cuts along Deadwood and Portage Creeks north of the Hot Springs fault expose similar highly weathered and oxidized gravels 5 to 20 ft below younger Quaternary gravels.

RECONNAISSANCE SAMPLING OF THE CROOKED CREEK GRAVELS

Placer-gold Deposits

The average tenor of gold-bearing gravels mined in Crooked Creek downstream from the confluence of Bedrock Creek to the town of Central is relatively low. Miners report values ranging from \$2.50 to \$5.00/yd³ (at \$350.00/oz) along this segment of Crooked Creek. Although pay may occur in any part of the upper gravel (and rich pockets do occur), well-defined pay streaks seem to be exceptions. The highest values seem to be concentrated in the top 2 or 3 ft of the gray gravel. The gold in the gravels located downstream from the Hot Springs fault has probably been reconcentrated from that in the former fan of Crooked Creek, which has been subsequently incised to a depth of 100 to 120 ft by the modern stream. Trenches cut into fan-terraces that flank the modern stream confirm the presence of gold (in sub-economic concentrations) in the fan.

Our panning tests of samples taken from the walls of placer-mine cuts showed that the vertices of ice-wedge casts and buried channels that penetrate the highly weathered older gravel and are filled by younger gray to brown gravel produced the most color per pan. Unfortunately, miners are confronted with the problem of how to mine the higher grade pockets without getting an undesirable admixture of clay-rich lower gravel. Clay in the lower gravel does not break up easily in wash plants and tends to clog riffle sets in sluice boxes, which increases fine gold loss.

Characteristics and Distribution of Crooked Creek Gold

Most gold recovered from mining operations on Crooked Creek downstream from the Hot Springs fault is fine grained, flattened, and highly abraded. Flattened grains are commonly curved or hooked, probably due to molding between gravel clasts. Gold fineness averages about 870 and tends to increase gradually downstream from the Hot Springs fault; average grain size decreases accordingly.

Discussions with local miners disclosed that both gold fineness and particle-size distribution change abruptly on the upstream side of the Hot Springs fault. This location is also roughly coincident with the head of the abandoned and incised alluvial fan. Upstream from the fault, average gold fineness drops below 840 with an accompanying increase in grain size. The gold tenor of the gravels is also relatively lower above the fault up to the confluence of Porcupine and Mammoth Creeks.

PLACER-GRAVEL AND CONCENTRATE EVALUATION

Primary Objectives

Due to the lack of funds and lead time, the 1985 placer sampling phase of the Crooked Creek diamond study was designed around the mining equipment and operations that were active on Crooked Creek or nearby claims. Our chief objective was to obtain concentrate samples from the diamond discovery sites in an attempt to recover diagnostic indicator minerals (and additional diamonds) for grade and quality studies.

An equally important goal was to accumulate mineralogic and petrologic information that could provide additional insight on the provenance of the gravels and the origin and travel paths of the diamonds.

Background

As previously discussed, we have no reliable data on diamond concentrations in the Crooked Creek gravels due to the diamond-loss factors associated with high-production sluice plants and the lack of records on the relative amount of lower vs. upper gravel that was run through sluice plants on Crooked Creek. We assume that an unknown number of diamonds may have been discharged into the tailings during the processing of over 1,000,000 yd³ of Crooked Creek gravel from 1980 to 1986.

Worldwide exploration experience demonstrates that reliable diamond-placer evaluations demand large samples (thousands of cubic yards) and carefully engineered diamond recovery plants. None of these options were available on Crooked Creek or nearby claims at the time of this reconnaissance, with the exception of a small jig operated by Robert Cacy on Portage Creek (near Circle Hot Springs), and a small, portable grease table designed and constructed by A.H. Clough (U.S. Bureau of Mines).

Considering the above constraints, it is not surprising that more diamonds were not discovered during the evaluation of sluice, jig, and pan concentrates and tailings. However, we believe that the evaluation was adequate for the identification of the heavy-mineral suites in the upper and lower gravels, including the search for possible kimberlite- or lamproite-derived 'indicator minerals.'

Crooked Creek Mining Methods and Sample Recovery

During placer-mining operations on the Warren claims, pit-run gravel was fed into a wash plant that included a double-deck vibrating screen rated in

excess of 100 yd³/hr input feed. Punch-plate size on the wash plant was 5/8 in. Washed and sized material was shunted into two 4-ft by 14-ft sluice boxes with expanded metal riffles and 'astroturf' matting. The sluice gradient was set at 1.5 in./ft with a water-flow rate of 700 to 900 gal/min (figs. 8a,b).

Analyses of concentrates vs. tailings from this plant indicate that any diamonds retained must be viewed as 'accidental' because the feed rate, velocity, and gradient are such that relatively low-density rock and mineral fragments---including diamonds---stand very little chance of being caught in the riffle sets or astroturf. This plant was the most appropriate bulk-sampling system available, and samples were obtained from concentrates caught in the sluice box and in the tailings.

Significantly, the Warren diamond was found during a clean-up of a 'Ross'-type sluice coupled with a wash plant that had even higher feed rates and higher water velocities than the plant used during 1985. These conditions further emphasize the accidental nature of the Warren discovery.

Several methods were used to collect bulk samples from Crooked Creek gravels. A large volume of previously obtained sluice-box concentrates was readily available from the claim blocks where the Warren diamond was found, and representative splits were taken for diamond and indicator-mineral testing. Samples of sluice-box concentrates were also collected from the Regan claim where the 0.3 kt diamond was found in 1982. However, the 1985 mining operation on the Regan ground was a very large volume operation that used wash plants and sluices of the 'Ross' type, which are characterized by very high feed rates, high water velocities, and corresponding steep sluice gradients. Diamond retention would be accidental in such a system. The sample splits obtained from the Regan ground were from clean-up concentrates that reportedly represented approximately 100,000 yd³ of bank-run gravel.

Robert Cacy's 2-cell Pan-American-type jig was set up to recover fine gold. A vibrating-screen wash plant treated bank-run material before it was run through the jig, which had a bed of iron shot. Although this plant was not ideal for diamond exploration, it was more efficient obtaining heavy-mineral concentrates in the desired specific-gravity range than the sluice plants previously used on Crooked Creek.

DESCRIPTION OF SAMPLES

The following summary and table describe the samples obtained and tested during 1985 and 1986.

Pan Concentrates (1985)

Pan concentrates were obtained from the lower and upper gravels on the Warren and Regan claims, from tailings in the same localities, and from bed and bank gravels in the tributary streams of Crooked Creek. Care was taken not to winnow the sample to the usual heavy-mineral suite retained in gold evaluation (for example, gold, magnetite, sulfides, cassiterite, etc.) due to

a

b

Figure 8. Photographs of Warren sluice plant in operation on Crooked Creek showing a) the delivery of gravel with the front-end loader and b) the grade and design of the sluice boxes.

the relatively low specific gravity of diamonds and indicator minerals (3.3 to 3.5).

Sluice Concentrates (1985)

Concentrates from the clean-up of sluice boxes on the Warren and Regan claims were also obtained from the operators after the removal of gold and the more highly magnetic fraction.

Sluice Tailings (1985)

A 150-lb sample of <5/8-in. tailings derived from sluiced upper and lower gravels from the Warren claims was also collected for trial processing over the grease table and through an X-ray sorter.

'Pan-American' Jig Concentrates (1985)

Seventy yd³ and 12 yd³ of the upper (gray) and lower (yellow) gravel, respectively, were transported from the Warren property to the jig plant operated by Robert Cacy on Portage Creek. Hutch and jig-scalp samples were taken from the jig during the processing of both types of gravel. Attempts to retain the lower specific gravity---or middling---fraction during jig runs resulted in very large concentrate volume, a problem that was solved by periodic sampling of both hutch and bed-load fractions.

Hydraulic Jig Concentrates (1986)

In late summer 1986, following the discovery of the third (Manuel) Crooked Creek diamond, a small hydraulic jig manufactured by the Keene Company, under test by the U.S. Bureau of Mines (Fairbanks, Alaska), was transported to Crooked Creek for small-volume tests on the lower Crooked Creek gravels. Concentrates derived from approximately 3 yd³ of lower gravels were returned to the laboratory for analyses; these analyses are not yet complete.

SAMPLE ANALYSIS

Most sample analyses were conducted on concentrates returned to laboratories in Juneau, Alaska, and Fort Collins, Colorado. However, grease-table tests were conducted in the field, as described below.

Grease-table Tests

Heavy-mineral concentrates must be preconditioned for grease-table runs. First, the concentrate must be scrubbed, which serves two purposes: 1) aids in breaking up and removing any clay that may be in the sample; and 2) removes surface coatings from the diamonds. Alluvial diamonds commonly have oxide coatings that may inhibit the hydrophobic (nonwetttable) characteristics of clean diamonds. Therefore, it is important to scrub the concentrate before it

Table 1. Information on concentrates obtained and evaluated in 1985-86.

Type	Source	Initial sample size	Reduced sample size
Pan concentrates (greater than 3.00 sp.gr.)	Gray gravel ^{1,2}	Miners pan	Several grams
	Yellow gravel ^{1,2}	Miners pan	Several grams
	Tailings ^{1,2}	Miners pan	Several grams
Clean-up concentrates	Bank-run gray and yellow gravel ^{1,2}	Unknown	300 lb
Sluice tails	Bank-run gray and yellow gravel ¹ ($<5/8$ in.)	Unknown	150 lb
'Pan American' jig concentrates	Bank-run gray gravel ¹	70 yd ³	800 lb
	Bank-run yellow gravel ¹	12 yd ³	200 lb
Hydraulic jig concentrates	Bank-run yellow gravel ¹	2 yd ³	30 lb

¹Warren claims

²Regan claims

is run over the grease table. The most common small-scale method of scrubbing and cleaning diamond concentrates involves the use of a cement mixer, steel grinding balls or stream pebbles and cobbles, and a slurry of the concentrate and water. Scrubbing time varies with the nature of the concentrate, but experience demonstrates that a minimum of 2 hr is necessary to break up clays and remove the surface coatings from placer diamonds. The concentrate should be removed from the cement mixer, sized, deslimed and immediately run across a grease table.

Grease-table Design and Operation

The grease table used for this work was designed by Clough and built in Juneau (figs. 3a, 3b). It consists of four inclined steps. Only the lower three steps are actually coated with grease. The top step receives the concentrates, which are then transported over the lower steps by water discharged at a spray bar at the head of the table. This table also employs an eccentric vibrator to accelerate movement of the concentrate down the steps while spreading the slurry across the steps to optimize diamond recovery. The vibrating motion also enhances the tendency of the diamonds to stick to the grease.

Concentrates can be deslimed prior to grease-table runs by wet sieving or by processing the concentrate across a vibrating screen directly onto the grease table. Use of a vibrating screen is strongly recommended for the treatment of large-volume samples.

The grease used for diamond recovery is a mixture of reagent-grade petroleum jelly (Vaseline) and paraffin. Depending on the ambient air and water temperature, the viscosity must be adjusted by altering the ratio of petroleum jelly and paraffin.

Air and water temperatures were so low during the Crooked Creek investigations that the use of paraffin was not necessary. The grease was readily applied to the table with a putty knife. At the end of each sample run, the grease and attached mineral and rock fragments were scraped off the steps and melted in a suitable container. The liquid fraction was decanted for reuse, and the residual concentrate was cleaned with an organic solvent and dried and checked for diamonds.

It is desirable to test the grease mixture with natural uncut diamonds to insure that the diamonds are adhering to the greased steps under local operating conditions. This was done during the Crooked Creek investigation using the Warren diamond, which adhered to the greased surfaces during each test. Therefore, it is presumed that clean diamonds, if present in concentrates, would have been retained on the grease table. Unfortunately, no additional diamonds were recovered in the grease-table runs.

X-Ray Screening of Selected Jig Concentrates

Several hundred pounds of 'Pan American' jig concentrates from the upper and lower Crooked Creek gravels (Warren properties) were shipped to Fort Collins, Colorado, for processing in Cominco American's X-ray ('Sortex') diamond sorter. Although representative fractions of concentrates from both gravels were processed, no diamonds were detected.

LABORATORY STUDIES OF CONCENTRATES

Sample Preparation and Examination

Microscopic examination of the concentrates was aided by heavy-liquid (methylene iodide) separations to reduce the volume of the samples and to insure that only those mineral phases with a specific gravity greater than 3.2 were retained for examination. Magnetic mineral phases were also removed from the concentrates prior to heavy-liquid separation.

Apparent Absence of Microdiamonds and Indicator Minerals

To date, neither microdiamonds nor confirmed indicator minerals have been identified in the pan, sluice, or jig concentrates obtained from Crooked Creek or its tributaries. However, many concentrate samples that were visually examined under the microscope represent relatively small initial gravel volumes, and some of these samples are actually splits from samples that were much too large for thorough study under the microscope.

CONCLUSIONS

1. Based on discussions with resident claim holders and miners and on our own investigations and findings, we conclude that the three Crooked Creek

stones are valid alluvial diamond discoveries that merit a follow-up exploration program.

2. Clearly, the large-volume wash plants currently used for gold recovery in placer-mining operations along Crooked Creek are poorly designed for the recovery of alluvial diamonds and cannot be used for the meaningful evaluation of diamond-bearing alluvial deposits. If one assumes that the previously discovered stones were not the only diamonds in the Crooked Creek gravels, it is probable that other diamonds have been discharged into the tailings during high-volume, steep-gradient sluicing operations.
3. Because both upper (gray) and lower (yellow) gravels were processed in the wash plants prior to discovery of the three diamonds, we do not know whether the diamonds are present in one or both gravel units. However, due to the high quality of the stones and the abundant percussion marks on the Warren and Manuel diamonds (which suggest a long and complicated alluvial history), we suspect that the diamonds may be in the yellow (older) gravels.
4. To date, we have not found the pyrope garnet, chrome-diopside, magnesian ilmenite indicator-mineral suite in concentrates taken from the gravels of Crooked Creek or its tributaries, but we have identified a wide assortment of garnets, pyroxenes, amphiboles, and grain-to-pebble-size aggregates of fine-grained magnetite (lodestone). None of these minerals have kimberlitic or lamproitic affinities. Therefore, no direct evidence suggests that the diamonds are from a nearby primary source.
5. Pebble and cobble lithologies in the the upper (gray) gravel indicate that these gravels are derived from the south, in the Yukon-Tanana Upland. Similar lithologies in the lower (yellow) unit also suggest a Yukon-Tanana Upland source, but deep weathering of the clasts and the clay-rich matrix connote a more complicated weathering history than that of the overlying gray gravels.
6. Although the Crazy Mountains (to the north) were also considered as a possible source for the Crooked Creek gravels, no major rock types in the east and west Crazy Mountains (Foster and others, 1983) are represented in the pebbles and cobbles of the Crooked Creek gravels.
7. Neither kimberlites nor lamproites have been recognized in the Crazy Mountains or Yukon-Tanana Uplands. However, alkaline basalts, syenites, lamprophyres, and igneous rocks with carbonatitic affinities have been described at various locations in the Yukon-Tanana Upland. These rock types comprise an alkaline igneous province that would be in harmony with the possible occurrence of kimberlitic or lamproitic rocks or both. The Yukon-Tanana terrane is a well-consolidated, stable cratonic block with a known Precambrian ancestry. These qualifications are conducive to the possible emplacement of kimberlites and lamproites.
8. Percussion marks on the exterior faces of the Warren and Manuel diamonds indicate long residence and transport time in the alluvial environment and a possible multicyclic history. The Regan diamond is somewhat

rounded, but rounding of this type can also occur during ascent and emplacement within the diatreme.

9. The possible multicyclic history of the Warren and Manuel diamonds suggests that they may have been derived from a fossil placer deposit in sedimentary host rocks. Prime candidates for such a source include metaconglomerates in the metamorphic terranes to the south, coarse clastic units in adjacent Tertiary deposits, and known Precambrian or lower Paleozoic conglomerates (or both) in the Crazy Mountains to the north. Tertiary basin deposits in the Crooked Creek drainage are adjacent to the trace of the Tintina fault and may be offset segments of successor basins that received detritus shed from the highlands during displacement along the Tintina fault.
10. The closest known diamond-bearing kimberlitic diatreme to Crooked Creek is located in the northern MacKenzie Mountains, Northwest Territories, Canada, about 125 mi northeast of Ross River (Godwin and Price, 1986). The diatreme intrudes Upper Cambrian to Lower Ordovician and lower Middle Ordovician silty limestones up to an unconformity at the base of the Upper Ordovician to Lower Silurian Mt. Kindle Formation. The regional tectonic setting is on the west margin of the North American plate (craton) in the MacKenzie Fold Belt. The kimberlite has an emplacement age of about 465 m.y. B.P. (Godwin and Price, 1986). Godwin confirms that microdiamonds were recovered from the diatreme. The tectonic setting is similar to that of the terranes on the Alaskan side of the Alaska-Yukon boundary (figs. 9, 10).
11. The best potential exploration targets for source kimberlite and lamproites appear to be the North American and Porcupine terranes north of the Yukon River and west of the Canada-USA boundary. If the diamonds are derived from reworked Tertiary sediments, the fault-bounded Tertiary basin north of Eagle could be the offset equivalent of the Tertiary basin that appears to be bounded by the two strands of the Tintina fault near Crooked Creek. Heavy-mineral concentrates from Tertiary gravels in these basins should also be prospected for possible diamonds and indicator minerals (figs. 9, 10).

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Figure 9. Tectonostratigraphic terrane map of western North America showing the edge of the North American plate and the locations of diamond-bearing kimberlites and recent Alaskan diamond discoveries. Barbed line represents approximate eastern limit of Cordilleran deformation (map from Ben-Avraham and others, 1981).

MAP UNITS		
<u>Terranes</u>		
CZ = Crazy Mountains	WC = Woodchopper Canyon	PC = Porcupine
KA = Kandik River		TZ = Tazitna
NAm = North American Plate		YT = Yukon-Tanana
<u>Other Map Units</u>
Cz = Cenozoic sedimentary deposits	

Figure 10. Simplified lithostratigraphic terrane map of the Yukon-Alaska International Boundary region showing the interrelationship of the North American plate and adjacent Alaskan lithostratigraphic terranes and the location of tectonic and geologic features discussed in the text (modified from Jones and others, 1984).

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