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Gold mineralization related to Cretaceous-Tertiary magmatism in west-central Alaska - a geochemical model and prospecting guide for the Kuskokwim region

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ABSTRACT

The occurrence of hypabyssal to plutonic dikes, stocks, and volcano-plutonic complexes at the headwaters of streams bearing placer gold in the Kuskokwim region of west-central Alaska led to early conclusions that hydrothermal systems associated with igneous rocks are the metal sources of these ore deposits. Subsequent discovery of lode precious metal deposits at the Golden Horn and the Nixon Fork mines added more credence to this hypothesis. These early spatial relations are supplemented by recent geochemical evidence. Plutonic rocks associated with gold are metaluminous, alkali-calcic, generally quartz monzonitic in composition, and appear to be ilmenite-series granitoids. Common characteristics for most of the plutonic rocks in the Kuskokwim region, regardless of shape or size of the plutonic body, are a reduced nature, as indicated by a low Fe_2O_3/ FeO value of the bulk rock; and a subalkaline to alkaline character, as shown by a commonly used alkalinity index. These characteristics are contrary to other studies that propose that oxidized, felsic magmas or oxidized magnetite series granitoids are genetically related to precious-metal deposits in volcano-plutonic arcs.

Ore deposits in the Kuskokwim region can be related to a vertically zoned model, with direct application to gold exploration. Mercury-dominated epithermal deposits, such as the Red Devil Mine, typify the structurally controlled, upper part of this model with an estimated 1500 meter maximum depth of formation. Gold values up to 10 ppm are found in cinnabar separates from mercury-dominant deposits. Stibnite-gold±cinnabar±tungsten quartz veins, such as those at Donlin Creek and Granite Creek, are examples of slightly deeper and/or higher temperature mineralization.

Gold deposits, such as the Golden Horn and Nixon Fork mines, typify deeper levels of mineralization. Gold is found in arsenopyrite-pyrite-scheelite-gold-sulfosalt veins or chalcopyrite-bornite-bismuth-gold skarns restricted to Late Cretaceous-early Tertiary quartz monzonitic stocks. Temperatures of formation up to 400°C have been estimated from fluid inclusions for this type of mineralization.

Tight clustering of Pb isotopic data supports interpretations that mineralization events are related to similar formation processes. Mineral deposits in the Kuskokwim region appear to be genetically associated with plutonic rocks of the Late Cretaceous-early Tertiary magmatic belt. Plutonic rocks appear to be the source of gold and other metals, while faults, breccias, and rock contacts acted as conduits to localize the ore metals in concentrations of potential economic significance.

Mining in the Kuskokwim region has produced at least 74.6 metric tons (2.4 million ounces) of gold, with byproduct silver, mercury, tungsten, and antimony over the past ninety years, mostly from placer deposits. Granitoid plutons in the Kuskokwim region provide favorable exploration targets for additional gold-bearing lode deposits or related placer occurrences.

INTRODUCTION

Ore deposits are commonly intimately associated with plutonic bodies of all ages and tectonic settings. Studies of magmatic-hydrothermal systems have led to two contrasting explanations for the association of ore deposits with plutonic rocks. One explanation is that plutonic rocks are structural conduits for ore deposit fluids from nonmagmatic or unknown sources; or the igneous body primarily serves as a heat and fluid pump to leach metals and associated elements from surrounding country rocks (Newhouse, 1942; Titley, 1987; Roslyakova et al., 1988; Nesbitt and Muehlenbachs, 1989; Nesbitt et al., 1989; Wyman and Kerrich, 1989; Nesbitt, 1991). The other explanation is that igneous rocks are the source of fluids, gold and other metals (Gottfried et al., 1972; Tilling et al., 1973; Keith, 1983; Mutschler et al., 1985; Keith and Swan, 1987; Leveille et al., 1988; Newberry et al., 1988; Burrows and Spooner, 1989; Rock et al., 1989; Sillitoe, 1989). Plutons probably act in both of these roles in different areas, in places simultaneously, which adds much difficulty to paragenetic interpretations of the plutonic rocks and mineralization.

The basic premise of the present magmatic-hydrothermal theory is that as a magma crystallizes, fractionation or other processes produce melts progressively enriched in volatiles and metals. Processes that lead to fluid release and crystal-melt and fluid-melt fractionation of critical elements, mainly metal species and volatile complexing agents, are at least as important, if not more important, as the initial magma chemistry to ore formation (Burnham, 1979; Hannah and Stein, 1990; Newberry et al., 1990; Candela, 1992). For example, granitic plutons associated with W skarn or Sn greisen-skarn deposits in the Fairbanks, Alaska area were shown by Newberry et al. (1990) to represent magmas with similar origins and source materials, but differences in crystallization environment and timing of vapor loss produced different metallogenic signatures. Volatiles and metals exsolved from igneous rocks can form a variety of ore deposits, such as veins, disseminated, skarn, and replacement deposits, generally depending on factors such as local lithologic and structural regimes.

Some recent studies have begun to characterize the geochemistry of intrusions related to precious metal deposits. There appear to be two main contradictory schools concerning the geochemical characteristics of igneous rocks related to gold deposits. A high degree of alkalinity in conjunction with low oxidation state has been suggested to indicate gold favorability (Mutschler et al., 1985; Keith and Swan, 1987; Leveille et al., 1988; Newberry et al., 1988; Rock et al., 1989; Schwab and Keith, 1989). However, other authors argue that the most likely sources for Au-bearing fluids in Archean or porphyry gold deposits are oxidized, CO_2-rich, felsic magmas (Sillitoe, 1979; Cameron and Carrigan, 1987; Cameron and Hattori, 1987; Hattori, 1987; Blevin and Chappell, 1992). Also, magnetite series granitoids, characterized by relatively oxidized nature, are proposed to be genetically related to all significant base- and precious-metal deposits in volcano-plutonic arcs (Ishihara, 1981).

This paper explores possible genetic relations between gold deposits and their associated plutonic rocks in the Kuskokwim region of Alaska. The objectives are to document empirical relationships between gold mineralization and magma chemistry and to provide a model for ore deposits in the study area. This investigation covers about 25,900 km^2 (10,000 mi^2) in west-central and southwestern Alaska, and includes data from areas of the Medfra, Ophir, McGrath, Iditarod, and Russian Mission quadrangles (Fig. 1).

Interest in west-central Alaska has been stimulated by the occurrence of many intermediate to felsic plutons and abundant placer gold production over a 77,700 km^2 (30,000 mi^2) province. Mining in the Kuskokwim region of west-central Alaska (Fig. 2) has produced at least 74.6 metric tons (2.4 million ounces) of gold, about 12.4 metric tons (440,000 ounces) of byproduct silver, nearly 41,000 flasks of mercury, and significant byproduct tungsten, and antimony over the past ninety years, mostly from placer deposits (Bundtzen et al., 1986; 1987). The presence of igneous rocks (some with gold-quartz veins, or gold-bearing polymetallic sulfide-quartz veins) at the sources of placer gold (± other metals) -rich streams in the Kuskokwim area caused miners and early geologists to conclude that igneous rocks are the metal sources (including Eakin, 1913, 1914; Brooks, 1916; Mertie and Harrington, 1916, 1924; Mertie, 1936). This same reasoning is echoed in later work by Bundtzen and Miller (1989, 1992), Bundtzen et al. (1992a), and Miller et al. (1989). These conclusions are largely based on field relationships, with little additional support. However, at Flat (southwestern Iditarod quadrangle, Fig. 1), Bull (1988) concluded, by studying minor and trace element trends, that metals in the ore deposits were derived from the igneous system(s). Elements enriched in ore (Au, As, Sb, W) are also enriched in halos surrounding the plutons, and these elements increase with increasing SiO_2 content in the plutonic suite.

Despite recognition of an association between igneous rocks and placer gold deposits in the Kuskokwim region, very little geochemical data and limited descriptive data on this area are present in the literature. The limited previous work has concentrated on 15 minute scale quadrangles, with little synthesis of material from adjacent areas. This incomplete and dispersed database did not facilitate recognition of systematic patterns of mineralization present throughout the Kuskokwim Mountains. This paper relies upon the work of previous investigators in the Kuskokwim region and attempts to consolidate those data with new data to evaluate the premise that plutonic rocks are a major source of gold in this part of Alaska.

Few lode gold deposits are known in the Kuskokwim region of Alaska, partly because of lack of intensive exploration and difficult access. Commonly, placer gold deposits in streams and creeks draining plutonic-cored mountains define those plutons as gold producing. Placer exploration in western Alaska was probably most intense during the early 1900s. Historically, placer miners in the Kuskokwim region looked for frozen ground when considering placer mining because the preferred mining technique was drift (underground) mining in the early 1900s. Typical of placer districts throughout Alaska, gold was first recovered by hand methods; scraper plants and floating dredges were introduced later (by 1920), and bulldozer-dragline sluicing operations commenced in the 1930s (Bundtzen et al., 1987). This last phase has continued to be the principal extraction method. Permafrost areas were probably more extensively explored and drift mined, while mining of thawed ground was dominantly by large, floating dredges. This style of mining dominated gold production during the period from about 1920 to the late 1950s, with the last floating operation discontinued in 1968. Streams with low discharge were unfavorable for dredge mining and even today are difficult to work by various bulldozer-sluice box methods. Therefore, stream characteristics and geomorphology are often factors when considering past placer activity as indicative of gold potential or endowment of the Kuskokwim Region. From the preceding, it is apparent that factors affecting placer development also affect pluton discriminant criteria.

REGIONAL GEOLOGY

The regional geology of the study area (Fig. 3) is described by Decker et al. (1994) and Patton et al. (1994). Precambrian metamorphic rocks, including crystalline rocks of the Yukon-Tanana Terrane, occur in the northern Kuskokwim Mountains and serve as depositional basement for Paleozoic units of the Ruby, Innoko, and Farewell Terranes (Silberman, et al., 1979; Bundtzen and Gilbert, 1983; Dillon et al., 1985; Decker et al., 1994; Moll-Stalcup, 1994). The Farewell Terrane, a nearly continuous sequence of Paleozoic continental margin rocks over 5,500 m thick (Patton et al., 1980; Dutro and Patton, 1981) underlies much of the southwestern Alaska Range and northern Kuskokwim Mountains and unconformably overlies metamorphosed Early Proterozoic sedimentary and plutonic units. The predominantly Upper

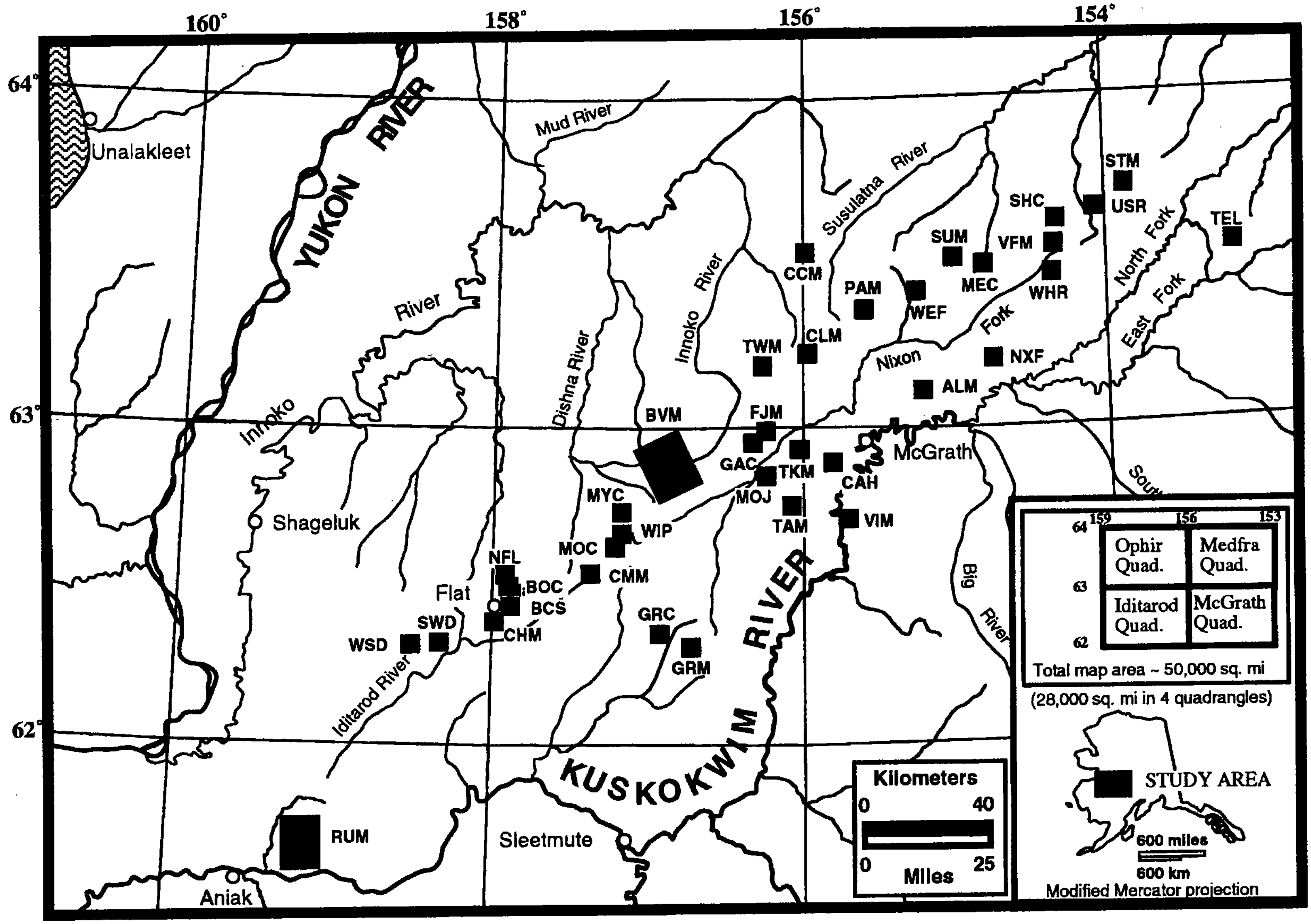

Figure 1—Location map of the Kuskokwim region. Black rectangles are plutonic areas mentioned in text and Table 1. Location abbreviations are defined in Appendix 1. Figure inset shows location of study area related to the State of Alaska and the main 1° by 3° quadrangles covered by this study. Map also includes the major rivers of the region and town locations.

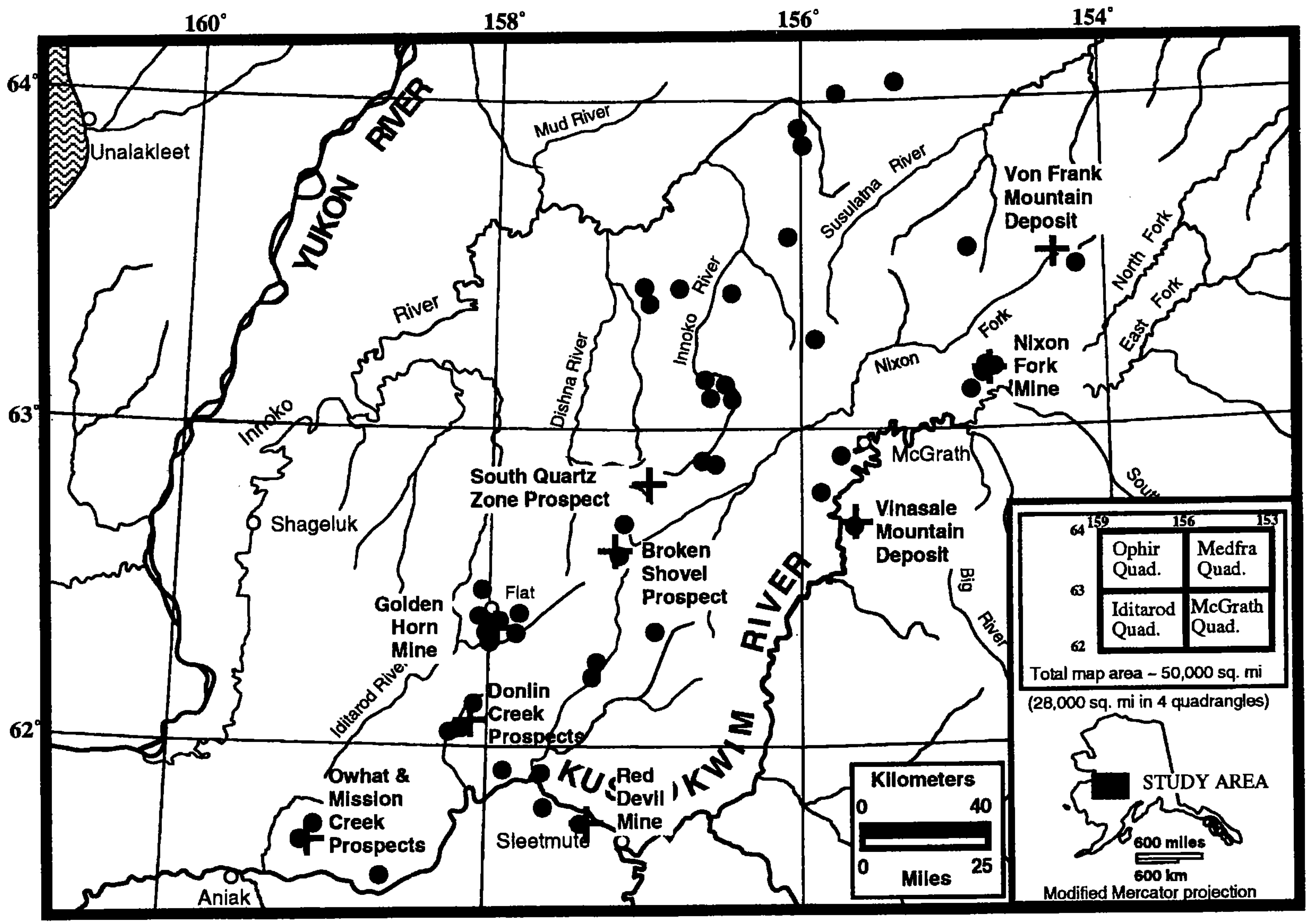

Figure 2–Locations of placer gold occurrences and important precious metal lode occurrences and mines in the Kuskokwim region. Base map is same as Figure 1. Shaded circles indicate locations of placer gold occurrences. Crosses indicate locations of lode prospects and mines mentioned in the text. Placer gold occurrences are from Maddren (1909, 1911) and Cobb (1973, 1974, 1976).

Cretaceous Kuskokwim Group, a post-accretionary basin-fill flysch sequence, is the most extensively exposed unit in the region (Fig. 3). The Kuskokwim Group consists largely of interbedded lithic sandstone and shale, and in large part rests unconformably on all older rock units of the region (Cady et al., 1955; Decker and Hoare, 1982; Bundtzen and Gilbert, 1983; Decker, 1984).

Two major northeast-trending faults traverse southwest Alaska, the Denali-Farewell fault system to the south, and the Iditarod-Nixon Fork fault to the north (Fig. 3). Late Cretaceous and Tertiary right-lateral offsets of 90 to less than 150 km characterize both faults (Bundtzen and Gilbert, 1983; Miller and Bundtzen, 1988).

The Kuskokwim Mountains are one of several Late Cretaceous to early Tertiary magmatic belts found throughout southern and western Alaska (Wilson, 1977; Hudson, 1979; Shew and Wilson, 1981). The Kuskokwim Mountains belt consists of calc-alkaline to alkaline andesitic to rhyolitic volcanic fields, isolated calc-alkaline stocks, and sub-alkaline to alkaline volcano-plutonic complexes (Moll-Stalcup, 1994). Plutonic rocks of the Kuskokwim Mountains magmatic belt extend over a northeast-trending area of approximately 900 km by 200 km (northern and central parts of this belt are shown in Fig. 3). Table 1 list selected plutonic rock analyses from the Kuskokwim Mountains. All igneous K-Ar age dates from the Kuskokwim Mountains range from 58 to 77 Ma, while plutonic K-Ar age dates range from 61 to 73 Ma (Szumigala, 1993).

Plutonic rocks of the Kuskokwim region have many typical geochemical characteristics of granites from volcanic arcs as defined by Pearce et al. (1984). These include: high-K or shoshonitic series affinity, biotite ± hornblende as the dominant ferromagnesian mineral(s), and variations from metaluminous to slightly peraluminous compositions. Major and trace element data are typical of arc-related calc-alkaline igneous rocks (Perfit et al., 1980; Gill, 1981) and suggest a common source for the Late Cretaceous to early Tertiary plutonic stocks and volcano-plutonic complexes. REE patterns are similar for plutonic and volcanic rocks from across a wide part of the Kuskokwim region, suggesting a common petrogenesis for many igneous centers.

Petrographic and chemical data for plutonic rocks of the Kuskokwim Mountains magmatic belt fit criteria for ilmenite series granitoids (Ishihara, 1981), including low Fe-Ti oxide content, ilmenite>magnetite, increasing Fe/Fe+Mg ratios in biotite with increasing SiO_2 content in the whole rock, and bulk Fe_2O_3/FeO ratios lower than 0.5. The plutonic rocks generally also have geochemical signatures compatible with I-type "granites": low Rb contents, Rb/Sr ratios, and $^{87/86}Sr$ values; and high K/Rb ratios, and Sr contents (Chappell and White, 1974).

Most plutons in the Kuskokwim area have quartz monzonitic to monzonitic compositions (Table 1) and are porphyritic. The fine-grained matrix texture of many plutonic rocks, well-developed contact metamorphic aureoles, sharp discordant contacts between igneous units, and common association of volcanic and plutonic rocks in igneous complexes indicate that intrusions were emplaced at shallow depths, probably within several kilometers of the paleosurface. Geobarometry calculations by Bull (1988) for plutonic rocks at Chicken Mountain (near Flat, Fig. 1) yield "maximum" emplacement depths of 1 to 4 km, which are probably representative for most plutonic areas throughout the Kuskokwim Mountains. Crystallization conditions calculated from coexisting biotite and ilmenite compositions (Bull, 1988) plot just below the quartz-fayalite-magnetite buffer assemblage (Wones and Gilbert, 1969).

KUSKOKWIM REGION GOLD DEPOSITS

Almost all plutons sampled for this study have minor to moderate amounts of propylitic alteration, dominated by secondary chlorite, epidote, and calcite. Clinopyroxene commonly has a halo of biotite, or is altered to a mixture of chlorite+opaques±amphibole±calcite. Many plutons in the Kuskokwim region also have secondary tourmaline replacing feldspar phenocrysts and matrix. Secondary tourmaline is commonly seen as spots and rosettes in most plutonic rocks, but tourmaline also occurs as almost complete replacements of plutonic rocks (examples include areas of the Beaver Mountains and the Russian Mountains) and as breccia matrix with plutonic rock clasts. Other types of alteration are minor, but locally important clay or sericite occur near veins and mineralized structures at numerous localities throughout the region. Also, replacement of feldspar phenocrysts by axinite in plutonic and volcanic rocks is common in parts of the Beaver and Russian Mountains (Bundtzen et al., 1988; Bundtzen and Laird, 1991; Szumigala, 1995).

Sixty three plutonic rock samples from the Kuskokwim region were analyzed for precious metal contents. Most of the plutonic rocks do not contain detectable gold or silver, at detection limits of 2 to 5 ppb Au and 0.2 ppm Ag. Gold was detected in samples from the Willow pluton (≤17 ppb), several sites in the Beaver Mountains (≤8 ppb), Granite Creek (≤29 ppb), and the Maybe Creek pluton (≤15 ppb). Determined values are at or near the detection limit, so accuracy is in doubt. Many of the plutonic rocks from the Flat area are reported to contain gold up to 58 ppb Au (Bull, 1988). The background concentration of Au in unaltered igneous rocks is generally less than 4 ppb (Tilling et al., 1973; Yingjun et al., 1983; Crocket, 1991), which is lower than the detection limits for analytical techniques reported in this study.

Gold has been found in polymetallic veins within plutons and along plutonic contacts in the Flat area, at the Broken Shovel prospect, and in the Beaver and Russian Mountains; in skarn at Nixon Fork; in shear zones at Granite Creek; and associated with hypabyssal and volcanic dikes at Donlin Creek and the Independence Mine (Cobb, 1976; Nokleberg et al., 1987; Nokleberg et al., 1994). The Nixon Fork mining district and the Golden Horn Mine (Fig. 2) have been chosen to characterize the regional style of mineralization because they are the best studied occurrences of lode gold mineralization, as well as having the most production. Gold deposits at Vinasale

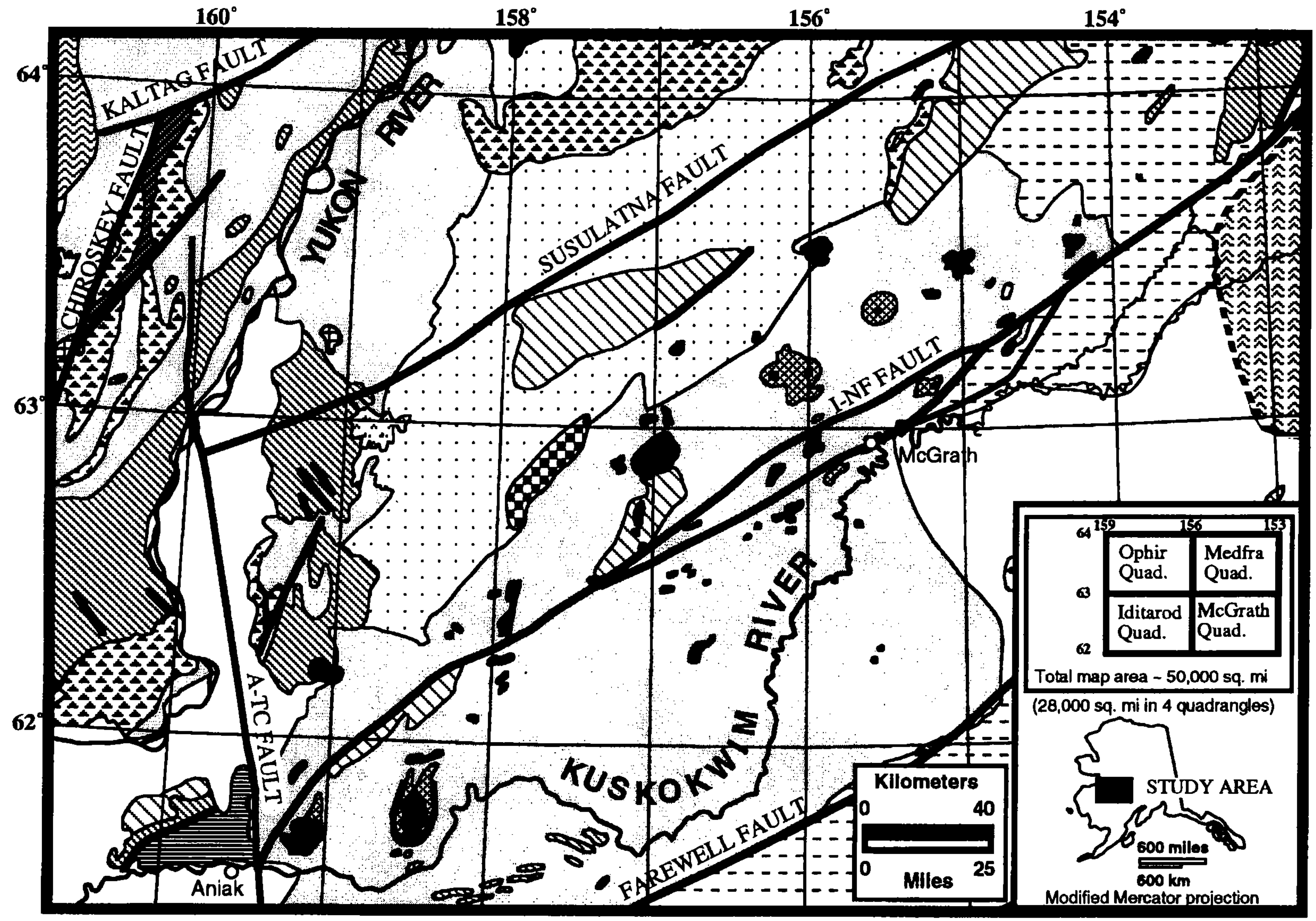

Figure 3—Kuskokwim region geologic map. Base map is same as Figure 1. Geology modified from Beikman (1980), with additions from Chapman et al. (1985), Patton et al. (1980), Gemuts et al. (1983), Miller et al. (1989), and Bundtzen et al. (1992a). Note the belt of Late Cretaceous-early Tertiary intrusive rocks and volcano-plutonic complexes trending from the upper right hand corner to the lower left hand corner of the figure.

Explanation of Map Symbols For Figure 3

- Quaternary Deposits
- Quaternary-Tertiary volcanic rocks
- Middle Tertiary continental deposits
- Late Cretaceous-Early Tertiary intrusive rocks
- Late Cretaceous-Early Tertiary volcanic rocks
- Late Cretaceous-Early Tertiary felsic volcanic rocks
- Late Cretaceous-Early Tertiary volcanoplutonic complexes
- Cretaceous intrusive rocks
- Cretaceous Kuskokwim Group
- Cretaceous and Jurassic rocks (black clastic turbidite)
- Jurassic, Triassic, and Permian volcanic rocks
- Mesozoic and Paleozoic rocks
- Farewell terrane (combination of Nixon Fork and Dillinger terranes)
- Paleozoic sedimentary and volcanic rocks (Ruby and Innoko terranes)
- Precambrian and early Paleozoic Yukon-Tanana terrane
- Early Proterozoic Idono Complex (metasedimentary and metaplutonic rocks)
- Fault
- Minchumina Suture
- Contact
- I-NF Iditarod-Nixon Fork Fault
- A-TC Aniak-Thompson Creek Fault

Mountain and Donlin Creek are recent discoveries and these deposits also provide important clues to understanding the regional metallogenesis. Gold prospects in the Beaver Mountains have been described in Szumigala (1995) and gold prospects associated with volcanic dikes have been discussed in Szumigala (1993).

Nixon Fork Gold Deposits

Gold skarns are associated with the 68 to 70 Ma Mystery Creek Stock at Nixon Fork in the Medfra quadrangle (Fig. 2), about 56 km (35 mi) northeast of McGrath. The deposits are adjacent to one of several plutons along the Iditarod-Nixon Fork Fault in an area largely covered by soil and vegetation. The skarn deposits were located by tracing placer gold (with native bismuth) deposits upstream to lode sources (Brown, 1926). This mineralization is one of few economically significant lode occurrences found within the Kuskokwim region.

The Nixon Fork mines produced approximately 1.8 metric tons (59,000 oz) of Au, with Cu, Ag, and minor Bi from 1917 to 1963 (Nokleberg et al., 1987; Newkirk et al., 1990; Bundtzen et al., 1992b). The total tonnage of ore mined has never been ascertained, but the average ore grade of several shipments in the 1920's was 46.9 g/t (1.5 oz/ton) gold, 2.6 percent copper, 62.5 g/t (2.0 oz/ton) silver, with bismuth credits (Bundtzen et al., 1986). Current measured and indicated resources at Nixon Fork are 114,995 short tons at 1.445 opt Au, containing 166,181 ounces of gold (unpublished 1994 Nevada Goldfields Inc. news release). Diluted recoverable reserves contain 154,517 ounces of gold.

Cretaceous age argillite and minor quartzite (metamorphosed lithic sandstone) of the Kuskokwim Group are found on the southwest edge of the Mystery Creek Stock. The dominant sedimentary units and hosts for skarn deposits are Middle and Upper Ordovician shallow water limestone and dolomite of the Telsitna Formation (Dutro and Patton, 1981). The Telsitna Formation in the Nixon Fork area consists predominantly of light gray to black limestone that ranges from thick-bedded and fine-grained to thin-bedded, silty, and micritic. Dolomite

Table 1—Major and trace element data of selected Kuskokwim plutonic rocks.

Location	Sample #	IUGS Rock Type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI *	Total
STM (1)	78PA53E	quartz diorite	55.80	0.92	18.60	2.42	3.54	0.10	4.20	7.61	3.47	1.56	0.20	1.54	99.96
VFM (5)	79PA144	monzonite	56.20	0.87	17.30	1.67	5.06	0.12	3.60	5.76	3.71	3.94	0.40	0.70	99.33
CCM (6)	78PA7	monzonite	54.99	0.91	16.56	1.43	5.85	0.15	4.32	6.37	3.82	3.77	0.61	0.54	99.32
SUM (7)	75PA23E	granite	73.32	0.25	14.15	0.30	1.44	0.04	0.45	1.69	3.79	3.86	0.07	0.42	99.78
PAM (11)	79PA113C	quartz monzodiorite	59.80	0.71	15.20	1.11	4.71	0.07	4.10	5.26	3.24	2.76	0.30	1.93	99.19
NXF (12)	79PA46	quartz monzonite	61.10	0.91	16.40	2.23	2.73	0.08	2.90	4.74	3.77	4.02	0.30	0.72	99.90
NXF (12)	78NF20	quartz monzonite	64.18	0.83	15.89	0.96	3.36	0.07	1.81	3.21	3.48	4.27	0.23	0.68	98.97
NXF (12)	88ZNF02	granite	65.65	0.66	16.30	1.98	1.74	0.06	1.47	2.68	3.66	4.49	0.20	0.70	99.59
NXF (12)	89ZNF28	quartz monzonite	57.70	1.51	16.25	1.97	4.80	0.11	2.42	4.97	4.09	3.69	0.50	0.10	98.11
CLM (13)	79PA30C	quartz monzodiorite	58.70	1.02	17.20	0.66	6.39	0.14	3.80	5.05	2.70	2.39	0.30	0.71	99.06
TWM (14)	90ZTM1031	quartz monzodiorite	61.00	0.56	13.80	1.06	4.30	0.12	5.55	5.53	2.64	3.28	0.06	1.00	98.90
GAC (17)	89ZGA9152	granodiorite	64.30	0.49	16.06	1.23	2.65	0.09	1.87	3.97	3.31	3.01	0.36	1.38	98.72
CAH (18)	78BT379	monzonite	56.17	0.84	17.91	1.16	5.83	0.14	3.34	4.99	3.73	4.00	0.40	1.10	99.61
TKM (19)	78BT461	monzonite	56.20	0.93	17.17	1.65	5.17	0.13	4.43	6.12	3.47	3.79	0.48	0.47	100.01
BVM (20)	90ZBM1014	granite	64.00	0.63	14.80	1.47	3.40	0.10	2.85	3.60	2.67	4.55	0.30	1.08	99.45
BVM (20)	90ZBM1016	quartz monzonite	62.60	0.52	19.10	1.19	1.05	0.04	0.98	3.84	3.42	5.32	0.41	1.01	99.48
BVM (20)	90ZBM1024	granite	71.85	0.28	14.10	0.92	1.67	0.04	0.48	0.98	2.88	6.27	0.06	0.10	99.63
MOJ (21)	89ZMJ6466	quartz monzodiorite	61.59	0.61	17.28	1.56	3.09	0.10	2.87	4.66	3.48	3.17	0.25	0.40	99.06
MYC (23)	89ZMC6471	granodiorite	63.99	0.61	14.84	1.39	2.96	0.09	4.23	3.61	2.86	3.82	0.24	0.60	99.24
WIP (24)	89ZWP6470	granite	62.47	0.80	16.13	1.05	3.34	0.10	3.63	3.38	3.26	4.30	0.27	0.40	99.13
VIM (25)	90ZVM1000	granite	66.13	0.42	16.79	1.28	1.42	0.07	1.22	2.28	3.71	4.18	0.22	1.10	98.82
VIM (25)	77BT257	granodiorite	66.69	0.46	16.30	0.81	2.34	0.07	1.60	3.32	3.71	3.97	0.23	0.58	100.08
MOC (26)	89ZBS6474	quartz monzonite	61.20	0.68	14.50	0.99	4.10	0.13	4.46	3.92	3.09	4.30	0.28	1.71	99.36
CMM (27)	89ZCM6459	quartz monzodiorite	57.40	0.62	14.40	0.65	5.80	0.15	5.76	6.34	2.81	3.34	0.11	1.32	98.70
BCS (30)	89ZGH6452	monzonite	53.00	0.55	13.00	1.54	5.60	0.15	9.80	6.54	2.80	3.30	0.47	1.89	98.64
BCS (30)	81BTFM	quartz monzonite	60.96	0.50	15.74	0.78	3.44	0.08	4.24	3.29	3.93	4.47	0.30	1.27	99.00
BCS (30)	89BT2	monzonite	52.70	0.72	12.50	1.40	6.20	0.10	12.30	6.73	2.35	3.02	0.41	0.85	99.28
CHM (31)	86KB52	monzonite	57.14	0.73	16.67	5.81	T	0.10	4.77	4.78	3.91	5.16	0.72	0.70	100.49
CHM (31)	86KB1	granite	67.94	0.35	15.16	0.71	1.86	0.03	1.27	1.30	3.52	5.20	0.20	0.78	98.32
CHM (31)	88BT51	monzodiorite	49.90	0.82	10.90	0.79	8.30	0.21	14.00	8.63	1.50	2.14	0.42	0.00	97.61
CHM (31)	84MSL155	granodiorite	65.29	0.40	15.45	4.16	T	0.07	2.75	3.14	3.72	3.50	0.23	0.78	99.49
GRC (32)	89ZGC6433	granodiorite	65.04	0.55	15.68	1.51	2.77	0.09	2.68	3.95	2.78	3.17	0.18	0.90	99.30
RUM (36)	88BT73	quartz syenite	65.90	0.47	16.25	1.07	1.97	0.06	0.97	2.00	3.84	5.80	0.18	1.35	99.86

Location abbreviations listed in Appendix. All FeO analyses are by the titrametric method. T= all Fe given as Fe_2O_3. LOI*= loss on ignition.
(+) All CIPW Norms and differentiation index (diff. index) recalculated by author for consistency.

	Sample no.	Quartz	Corundum	Orthoclase	Albite	Anorthite	Nepheline	Diopside	Hypersthene	Olivine	Magnetite	Ilmenite	Apatite	Diff. index	References
CIPW	78PA53E	7.59	0.00	9.37	29.83	31.06	0.00	4.77	11.56	0.00	3.57	1.78	0.44	46.79	1
Norms	79PA144	1.46	0.00	23.61	31.83	19.18	0.00	5.85	13.01	0.00	2.46	1.68	0.89	56.89	1
(+)	78PA7	0.00	0.00	22.55	32.72	17.11	0.00	8.90	9.28	4.16	2.10	1.75	1.35	55.27	2
	75PA23E	31.68	0.84	22.96	32.27	7.98	0.00	0.00	3.20	0.00	0.44	0.48	0.15	86.91	1
	79PA113C	12.31	0.00	16.77	28.19	19.31	0.00	4.49	15.18	0.00	1.65	1.39	0.67	57.26	1
	79PA46	10.63	0.00	23.95	32.16	16.09	0.00	4.50	6.97	0.00	3.26	1.74	0.66	66.74	1
	78NF20	17.08	0.26	25.67	29.96	14.67	0.00	0.00	8.79	0.00	1.42	1.60	0.51	72.71	2
	88ZNF02	19.77	1.04	26.83	31.32	12.12	0.00	0.00	4.29	0.00	2.90	1.27	0.44	77.91	3
	89ZNF28	6.20	0.00	22.25	35.31	15.39	0.00	5.29	8.55	0.00	2.91	2.93	1.11	63.76	3
	79PA30C	14.00	1.74	14.36	23.23	23.48	0.00	0.00	19.55	0.00	0.97	1.97	0.67	51.59	1
	90ZTM1031	12.89	0.00	19.80	22.82	16.46	0.00	9.01	16.22	0.00	1.57	1.09	0.13	55.51	3
	89ZGA9152	22.39	1.03	18.27	28.77	17.82	0.00	0.00	8.08	0.00	1.83	0.96	0.81	69.43	3
	78BT379	1.11	0.00	23.99	32.04	20.62	0.00	1.54	16.43	0.00	1.71	1.62	0.89	57.15	4
	78BT461	1.59	0.00	22.50	29.50	20.17	0.00	5.85	15.10	0.00	2.40	1.77	1.05	53.59	4
	90ZBM1014	18.55	0.00	27.33	22.97	15.21	0.00	0.78	11.08	0.00	2.17	1.22	0.67	68.85	3
	90ZBM1016	13.96	1.74	31.93	29.39	16.63	0.00	0.00	2.64	0.00	1.75	1.00	0.91	75.27	3
	90ZBM1024	27.72	0.94	37.23	24.48	4.49	0.00	0.00	3.13	0.00	1.34	0.53	0.13	89.43	3
	89ZMJ6466	14.23	0.25	18.99	29.84	21.78	0.00	0.00	10.86	0.00	2.29	1.17	0.55	63.06	3
	89ZMC6471	18.05	0.01	22.88	24.53	16.57	0.00	0.00	14.17	0.00	2.04	1.17	0.53	65.47	3
	89ZWP6470	13.45	0.62	25.74	27.94	15.20	0.00	0.00	13.34	0.00	1.54	1.54	0.60	67.13	3
	90ZVM1000	22.54	2.60	25.28	32.12	10.10	0.00	0.00	4.12	0.00	1.90	0.82	0.49	79.94	3
	77BT257	19.80	0.42	23.58	31.55	15.04	0.00	0.00	7.02	0.00	1.18	0.88	0.50	74.93	4
	89ZBS6474	11.12	0.00	26.02	26.77	13.31	0.00	3.84	15.48	0.00	1.47	1.32	0.63	63.92	3
	89ZCM6459	5.29	0.00	20.27	24.42	17.27	0.00	11.66	18.66	0.00	0.97	1.21	0.25	49.98	3
	89ZGH6452	0.00	0.00	20.16	24.49	13.60	0.00	13.44	14.49	9.31	2.31	1.08	1.06	44.64	3
	81BTFM	6.84	0.00	27.03	34.02	12.39	0.00	1.87	15.01	0.00	1.16	0.97	0.67	67.89	5
	89BT2	0.00	0.00	18.13	20.20	14.87	0.00	13.05	16.82	12.51	2.06	1.39	0.91	38.33	5
	86KB52	0.00	0.00	30.73	33.35	12.80	0.00	5.18	7.27	6.75	0.85	1.40	1.59	64.08	6
	86KB1	22.97	1.90	31.50	30.53	5.27	0.00	0.00	5.61	0.00	1.06	0.68	0.45	85.01	3
	88BT51	0.00	0.00	12.96	13.00	17.10	0.00	19.27	17.14	16.78	1.17	1.60	0.94	25.96	5
	84MSL155	18.43	0.39	21.02	31.99	14.31	0.00	0.00	11.31	0.00	1.23	0.77	0.51	71.45	5
	89ZGC6433	23.76	0.94	19.04	23.90	18.72	0.00	0.00	9.93	0.00	2.23	1.06	0.40	66.70	3
	88BT73	15.44	0.46	34.79	32.98	8.88	0.00	0.00	4.55	0.00	1.57	0.91	0.40	83.21	7

References- (1) Moll, USGS unpublished data, (2) Moll et al., 1981, (3) Szumigala, 1993, (4) Bundtzen, ADGGS unpublished data, (5) Bundtzen et al., 1992a, (6) Bull, 1988, (7) Bundtzen and Laird, 1991.

interbeds are blue-gray in color, fine- to medium-grained, and range in thickness from 1 to 44 m (3 to 145 ft). Carbonate rocks near plutonic bodies are contact metamorphosed to a slightly coarser grained marble and contain trace to about ten percent fine-grained, disseminated pyrite and pyrrhotite.

The Mystery Creek Stock, a 68 to 70 Ma, alkali-calcic, metaluminous quartz monzonite/quartz monzodiorite stock intrudes the Telsitna Formation at Nixon Fork (Herreid, 1966; Moll et al., 1981; Szumigala, 1993). The ferric/ferrous ratio is quite low, primary opaque content is low (generally less than 1%) and most of the opaques are ilmenite rather than magnetite. These and other results from petrographic studies indicate dry, reduced conditions of crystallization for the Mystery Creek Stock.

The poorly exposed stock has a crude elliptical shape covering 39 km^2 (15 mi^2), with known skarn bodies restricted to its western edge. Drillhole data (Battle Mountain Exploration Company, unpublished report, 1988) indicate that either the Mystery Creek Stock thins to the west, or that a large sill ranging in thickness from 17 to over 100 m (55 to over 300 ft) occurs along the western margin where quartz monzodiorite is very irregular in outline and has numerous apophyses. Other intrusive units, cutting both sedimentary rocks and the Mystery Creek Stock, include dikes of quartz porphyry, monzodiorite, and dacite. Many dikes are extensively sericitized and K-Ar dates of fine-grained white mica from these dikes are equivalent to the Mystery Creek Stock age (Szumigala, 1993).

Surficial exposures of mineralization are quite limited. Drill results by several mining companies, as well as observations made during mining, indicate that skarn bodies and economic precious metal values are apparently restricted to the immediate area of plutonic/marble contacts and to marble pendants in the plutonic rocks. Geophysical and soil sampling programs have failed to identify any skarn bodies beyond sixty meters (200 ft.) of plutonic exposures (Reed and Miller, 1971; Szumigala, Battle Mountain Exploration Co. unpublished report, 1988). All mining and most of the recent exploration effort has been restricted to the western margin of the Mystery Creek Stock. The sill-like form of the intrusion possibly restricted metasomatic fluids to the western margin.

The richest gold grades at Nixon Fork occur in oxidized skarn consisting of iron oxides-bismuthinite-quartz-calcite-clay minerals, with some remnant garnet, pyroxene, amphibole, and micas (phlogopite and chlorite). The association of gold with intense retrograde hydrosilicate alteration is typical for gold-bearing skarns (Theodore et al., 1991). However, prograde pyroxene-dominant skarn also contains significant gold associated with chalcopyrite, pyrrhotite, bismuth-telluride, and native bismuth (Larry Freeman, written comm., 1995). Skarn assemblages at Nixon Fork are both calcic and magnesian (cf. Zharikov, 1970; Einaudi and Burt, 1982), but calcic skarn is by far the dominant skarn type, accounting for more than ninety volume percent of total skarn.

Local compositional differences in the carbonate protolith control the skarn type and local conditions control the ultimate skarn mineralogy. At Nixon Fork, limestone (calcium carbonate) is much more common than dolomite (magnesian carbonate). Therefore, the skarn assemblages tend to be garnet±pyroxene±epidote±calcite (calcic skarn assemblage), rather than olivine or humite±talc±serpentine±phlogopite (magnesian skarn assemblage). The dominant calc-silicates in prograde skarn at Nixon Fork are garnet, pyroxene, and epidote, with locally important wollastonite. In several drillholes, a progression can be observed from marble to a spotted skarnoid consisting of carbonate (dominant mineral)-olivine or humite (altering to serpentine)-fluorite-periclase (generally altered to brucite)±phlogopite to garnet-pyroxene-epidote skarn.

Chalcopyrite is the dominant ore mineral found in prograde skarn at Nixon Fork, but other ore minerals include bornite, pyrite, magnetite, native bismuth, native gold, and numerous supergene minerals (including limonite, tenorite, malachite, chrysocolla, and azurite). Some of the plutonic rocks host auriferous quartz veinlets near contacts with skarn deposits (Tom Bundtzen, 1991, oral comm.).

The principal controls on skarn mineralization are a combination of bedding and structures peripheral to the main plutonic contact or in areas adjacent to dikes and apophyses splaying outward from the stock (Brown, 1926; Herreid, 1966; Newkirk et al., 1990). Local structures with N30°E to N50°E trends appear to be significant for localizing skarn bodies and gold mineralization. Ore bodies were generally irregularly shaped with vertical or horizontal dimensions of less than 30 m (100 ft) (Mertie, 1936). Ore at the 460 foot depth in the Garnet shaft, on the west side of the Mystery Creek Stock, occurred as large slabs cemented by secondary copper minerals and limonite in chimney-like caverns near a "tongue of quartz monzonite" (Jasper, 1961). The largest deposit and principal producer at Nixon Fork was the Whalen Mine, located in a roof pendant or enclave of carbonate rock within the southern part of the Mystery Creek Stock (Brown, 1926; Herreid, 1966).

Although the Nixon Fork skarn deposits are one of the few lode gold deposits in the Kuskokwim region, the possibility of other similar mineralization is limited to areas with carbonate units. Outcropping carbonate units are restricted to the Medfra quadrangle, effectively restricting exploration for similar skarn occurrences to the area surrounding and north of the Nixon Fork deposits.

Golden Horn Deposit and Other Ore Occurrences at Flat

The Iditarod Mining District ranks as Alaska's third largest producer of placer gold (Bundtzen et al., 1992a), and most mining has occurred within 16 km (10 mi) of the town of Flat (Nokleberg et al., 1987). The Flat area, 132 km (82 mi) southwest of McGrath (Fig. 2), has yielded approximately 46.6 metric tons (1.5 million oz.) of gold since mining began in 1909. Most gold production is from placer deposits, although the Golden Horn lode deposit was mined from 1925 to 1937 and produced 535 tons of Au-Ag-W-Pb ore yielding 84.2 kg (2,706 ounces) of gold, 81.5 kg (2,620 ounces) of silver, and 4,243 kg (9,336 pounds) of lead (Bundtzen et al., 1992a). All placer operations are on creeks that either begin at or cross a