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Precious Metals Associated with Late Cretaceous-Early Tertiary Igneous Rocks of Southwestern Alaska

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Abstract

Placer gold and precious metal-bearing lode deposits of southwestern Alaska lie within a region 550 by 350 km, herein referred to as the Kuskokwim mineral belt. This mineral belt has yielded 100,240 kg (3.22 Moz) of gold, 12,813 kg (412,000 oz) of silver, 1,377,412 kg (39,960 flasks) of mercury, and modest amounts of antimony and tungsten derived primarily from Late Cretaceous-early Tertiary igneous complexes of four major types: (1) alkali-calcic, comagmatic volcanic-plutonic complexes and isolated plutons, (2) calc-alkaline, meta-aluminous reduced plutons, (3) peraluminous alaskite or granite-porphyry sills and dike swarms, and (4) andesite-rhyolite subaerial volcanic rocks.

About 80 percent of the 77 to 52 Ma intrusive and volcanic rocks intrude or overlie the middle to Upper Cretaceous Kuskokwim Group sedimentary and volcanic rocks, as well as the Paleozoic-Mesozoic rocks of the Nixon Fork, Innoko, Goodnews, and Ruby preaccretionary terranes.

The major precious metal-bearing deposit types related to Late Cretaceous-early Tertiary igneous complexes of the Kuskokwim mineral belt are subdivided as follows: (1) plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits, (2) peraluminous granite-porphyry-hosted gold polymetallic deposits, (3) plutonic-related, boron-enriched silver-tin polymetallic breccia pipes and replacement deposits, (4) gold and silver mineralization in epithermal systems, and (5) gold polymetallic heavy mineral placer deposits. Ten deposits genetically related to Late Cretaceous-early Tertiary intrusions contain minimum, inferred reserves amounting to 162,572 kg (5.23 Moz) of gold, 201,015 kg (6.46 Moz) of silver, 12,160 metric tons (t) of tin, and 28,088 t of copper.

The lodes occur in veins, stockworks, breccia pipes, and replacement deposits that formed in epithermal to mesothermal temperature-pressure conditions. Fluid inclusion, isotopic age, mineral assemblage, alteration assemblage, and structural data indicate that many of the mineral deposits associated with Late Cretaceous-early Tertiary volcanic and plutonic rocks represent geologically and spatially related, vertically zoned hydrothermal systems now exposed at several erosional levels.

Polymetallic gold deposits of the Kuskokwim mineral belt are probably related to 77 to 52 Ma plutonism and volcanism associated with a period of rapid, north-directed subduction of the Kula plate. The geologic interpretation suggests that igneous complexes of the Kuskokwim mineral belt formed in an intracontinental back-arc setting during a period of extensional, wrench fault tectonics.

The Kuskokwim mineral belt has many geologic and metallogenic features similar to other precious metal-bearing systems associated with arc-related igneous rocks such as the Late Cretaceous-early Tertiary Rocky Mountain alkalic province, the Jurassic Mount Milligan district of central British Columbia, the Andean orogen of South America, and the Okhotsk-Chukotka belt of northeast Asia.

Introduction

PRECIOUS metal-enriched, polymetallic deposits associated with Late Cretaceous-early Tertiary igneous complexes form an important metallogenic region in western and southwestern Alaska. These deposits lie within a northeast-trending, elongate belt that encompasses much of southwestern and part of western Alaska and is herein referred to as the Kuskokwim mineral belt, named after the Kuskokwim Mountains, the principle geographic feature in the region. This paper (1) presents an overview of past mineral resource development, (2) summarizes the regional geologic setting, (3) briefly describes the nature of the Late Cretaceous-early Tertiary igneous rocks, (4) describes and classifies precious metal mineral deposits, (5) presents metallogenic and tectonic models, and (6) offers guidelines for future exploration.

The Kuskokwim Mountains form a broad northeast-trending belt of accordant rounded ridges and broad sediment-filled lowlands occasionally graced by rugged and locally glaciated, igneous-cored massifs. This study covers a region 550 km long by 350 km wide (192,500 km^2) extending from Goodnews Bay, on the extreme southwestern coast, to Von Frank Mountain, about 100 km northeast of McGrath (Fig. 1).

Mineralized volcanic and plutonic rocks of Late Cretaceous to early Tertiary age are widespread in the province and have been the source of rich placer gold deposits, the host for economic mercury-antimony lodes, and the focus of recent exploration for gold polymetallic, epithermal gold-silver, copper-molybdenum porphyry, and rare earth element (REE) resources of several mineral deposit types. Gray et al. (1997) describe the mercury deposits of the study area. This paper discusses the geology of the gold and silver-bearing deposit types.

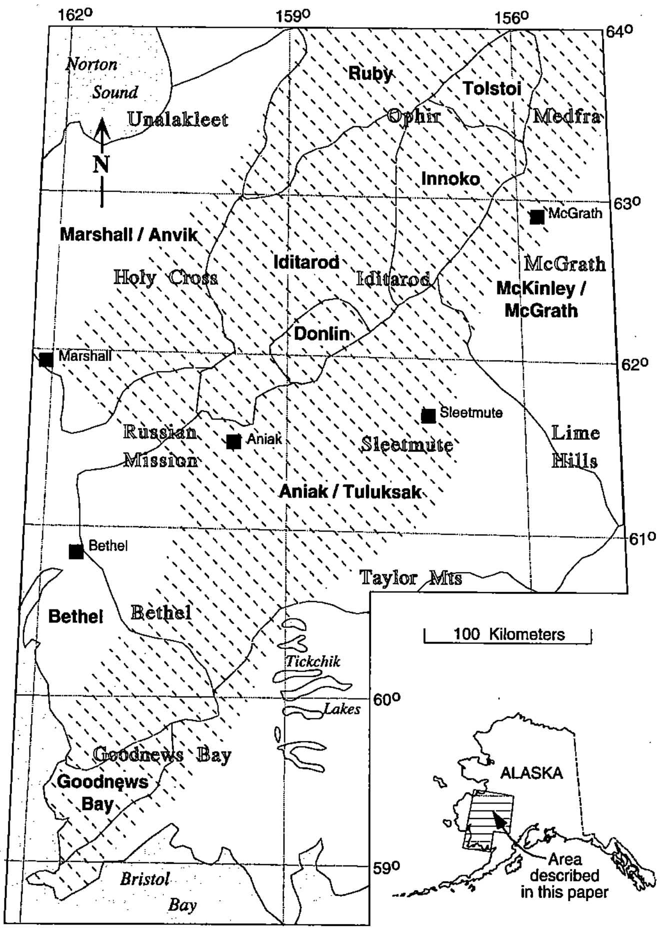


FIG. 1. Map of the Kuskokwim mineral belt (hatched pattern), showing principal settlements (solid squares), 1:250,000 quadrangles (outlined lettering), and boundaries of historic gold mining districts, as summarized by Ransome and Kerns (1954).

A brief history of mineral resource development

In the first half of the nineteenth century, Russians explored the southern Kuskokwim Mountains and in 1838 found cinnabar-stibnite deposits near Kolmakof Fort; this was the first mineral discovery made by Russians in Alaska (Spurr, 1900). The search for paying quantities of gold in the Kuskokwim mineral belt began with the Aniak discoveries of 1901. These were followed successively by the Innoko (1906), Iditarod (1909), Nixon Fork (1910), Marshall (1913), and Tolstoi (1916) discoveries. These placer gold rushes prompted a series of geologic and mineral resource investigations by the U.S. Geological Survey in the Kuskokwim River basin (Maddren, 1909, 1910, 1911; Eakin, 1914; Mertie, 1922; Mertie and Harrington, 1924). Placer gold is still being produced from all of these mining districts (Table 1). Mertie (1936) suggested that most placer gold deposits of the Kuskokwim mineral belt were associated with Tertiary plutons and stocks. Modern isotopic age dating indicates that these igneous bodies are Late Cretaceous to early Tertiary (Miller and Bundtzen, 1994; Wilson et al., 1994).

The next major period of mineral resource development concentrated on exploitation of several types of lode deposits—first, mesothermal polymetallic gold and epithermal mercury-antimony vein deposits and, later, strategic mineral deposits such as platinum at Goodnews Bay (see footnote in Table 1). Lode gold mining took place intermittently from 1911 to 1960. Mercury mining began in the 1920s, peaked in the 1950s, and had ceased by the mid-1970s.

The third period of mineral development was spurred by the high precious metal prices of the late 1970s and early 1980s, when modern exploration firms began to explore the region for bulk mineable gold deposits. Since the mid-1980s, significant new gold-silver resources have been proven at Donlin Creek, at Vinasale Mountain, and at the Golden Horn and Chicken Mountain deposits in the Iditarod-Flat district (Table 2).

Metallic mineral production has been confined to gold, mercury, antimony, tungsten, and silver. All but 2,140 kg (68,810 oz) of the total 100,240 kg (3.22 million oz) of gold mined in the Kuskokwim mineral belt was derived from placer deposits eroded from Mesozoic-Cenozoic igneous complexes (Table 1). Nearly 85 percent of the 1,377,412 kg (39,960 flasks) of mercury mined in the region was won from lodes in the Red Devil mine; the remaining production originated from a dozen, small, high-grade cinnabar lodes scattered throughout the Kuskokwim mineral belt. Modest amounts of tungsten, silver, and antimony were produced as by-products of gold and mercury mines, and almost all of the 12,813 kg (412,000 oz) of silver recovered was a by-product of placer gold refining (Table 1).

Regional Geology and Tectonic Setting

Rocks in the Kuskokwim mineral belt are broadly subdivided into two groups, by age and tectonic history: Lower Cretaceous and older fault-bounded terranes, and middle Cretaceous and younger overlap and basin fill assemblages of sedimentary and volcanic rocks, which were subsequently intruded by mafic to felsic plutons (Bundtzen and Gilbert, 1983; Decker et al., 1994; Miller and Bundtzen, 1994).

Proterozoic to Lower Cretaceous rocks crop out in fault-bounded belts that generally parallel the northeasterly structural grain of the region (Fig. 2). These older rocks can be grouped into four categories: (1) terranes or assemblages of continental affinity; (2) terranes formed near continental margins; (3) oceanic crust and subduction zone complexes; and (4) island-arc and related flysch sequences. The first category contains the oldest units in the region, represented by the Late Archean(?) to Early Proterozoic Kilbuck terrane (Box et al., 1990) and Idono Complex (Miller et al., 1991). The Late(?) Proterozoic to Paleozoic Ruby terrane (Patton et al., 1994) lies east and north of the Idono Complex. These oldest lithologies form discontinuous fault-bounded rock sequences that lie along the northwestern edge of the Kuskokwim Mountains. Rocks that were deposited in a continental margin setting lie in the eastern and central parts of the Kuskokwim mineral belt and consist of parts of the Nixon Fork, Dillinger, and Mystic terranes, which have been collectively referred to as the "Farewell terrane" by Decker et al. (1994). The Nixon Fork and Dillinger terranes, which are characterized by Middle Cambrian to Devonian platform carbonate and deeper water carbonate-clastic rocks, respectively (Bundtzen

TABLE 1. Gold, Silver, and Mercury Production from the Kuskokwim Mineral Belt of Southwestern Alaska, by Mining District, 1900–1995

District	Total gold production (kg)	Placer gold (kg)	Lode gold (kg)	Silver (kg)	Mercury (kg)
Marshall-Anvik	3,835	3,835	NR	394	NR
Tolstoi	3,450	3,450	NR	335	NR
Innoko	18,441	18,436	5	2,012	NR
McGrath-McKinley	6,117	4,074	2,043	770	1,723
Iditarod[1]	48,494	48,402	92	6,789	55
Donlin	750	750	NR	66	51,710
Aniak-Tuluksak	16,893	16,893	NR	2,027	1,323,924[2]
Bethel	1,336	1,336	NR	300	NR
Goodnews Bay[3]	924	924	NR	120	NR
Total	100,240 kg (3,223,000 oz)	98,100 kg (3,145,000 oz)	2,140 kg (68,810 oz)	12,813 kg (412,000 oz)	1,377,412 kg (39,960 flasks)

Gold production data from Bundtzen et al. (1994, 1996); districts from Ransome and Kerns (1954); see Figure 1; NR = not recorded

[1] Includes production from the Flat, Moore, Julian, and Granite Creek camps

[2] Mercury production probably conservative; production from Kolmakof mine is unknown

[3] Also produced 19,935 kg (641,000 oz) of placer platinum-group elements derived from a zoned ultramafic complex of Jurassic age at Red Mountain

and Gilbert, 1983; Patton et al., 1994), and the Mystic terrane, which is a heterogeneous assemblage of Devonian to Lower Jurassic clastic, carbonate, and volcanic rocks (Jones et al., 1982; Decker et al., 1994), have probably been displaced from North American sources by right-lateral movement along the Denali-Farewell, Iditarod-Nixon Fork, Tintina, and related faults.

Paleozoic-Mesozoic oceanic crust and subduction assemblages occur primarily in the western half of the Kuskokwim mineral belt. As subdivided here, this group contains parts of the Innoko and Angayucham-Tozitna terranes composed of Devonian to Upper Jurassic oceanic crust and related sedimentary rocks (Patton et al., 1994); all of the Goodnews terrane, an Ordovician to Upper Jurassic subduction complex (Box, 1985; Decker et al., 1994); and the Tikchik terrane, a chaotic assemblage of Ordovician to Early Cretaceous blocks in matrix (Jones et al., 1987; Decker et al., 1994).

Island-arc and related flysch sequences, which are found throughout the Kuskokwim mineral belt, make up the last category of middle Cretaceous and older rocks. Included in this group are the Togiak terrane, composed of Upper Triassic to Lower Cretaceous volcanic and epiclastic rocks (Box, 1985; Box et al., 1993; Decker et al., 1994); the Nyac terrane, composed largely of volcanic and volcaniclastic rocks of Jurassic and Cretaceous age (Box et al., 1993; Decker et al., 1994); part of the Koyukuk terrane, which consists of Permian or older carbonate and clastic rocks and early Mesozoic igneous rocks, which are unconformably overlain by Jurassic-Cretaceous volcanic and volcaniclastic rocks (Patton et al., 1994); and a part of the Kahiltna terrane, an Upper Jurassic to Lower Cretaceous volcaniclastic turbidite-dominated basin sequence (Wallace et al., 1989; Decker et al., 1994).

Amalgamation of the lithotectonic terranes of western Alaska was completed prior to middle Cretaceous time (Decker et al., 1994; Patton et al., 1994). Subsequently, these older terranes were eroded and partly covered by terrigenous clastic rocks deposited into the Yukon-Koyukuk and Kuskokwim basins. Both basin fill sequences are middle to Late Cretaceous in age and have prograding turbidite, shallow-marine, and shoreline facies (Miller and Bundtzen, 1994; Patton et al., 1994), which suggest that both basins filled in by early Late Cretaceous time. The Yukon-Koyukuk basin deposits are largely volcaniclastic, reflecting erosion of the surrounding Koyukuk and Angayucham-Tozitna terranes (Patton et al., 1994). The regionally extensive Upper Cretaceous Kuskokwim Group was deposited primarily by turbidity currents into an elongate, probably strike-slip basin (Bundtzen and Gilbert, 1983; Miller and Bundtzen, 1994). Local interbedded tuffs and volcaniclastic sandstone in the Kuskokwim Group indicate a provenance sometimes similar to the Yukon-Koyukuk basin deposits, but much of the Kuskokwim Group is derived from a mixture of sedimentary and metamorphic terranes (Decker et al., 1994).

Volcanic-plutonic complexes, plutons, and extensive dike and sill swarms intrude and overlie the older terranes and the Cretaceous flysch basin fill sequences. These Late Cretaceous-early Tertiary igneous rocks host a variety of mineral deposits that form the Kuskokwim mineral belt. Small, isolated fields of Late Tertiary alkali-olivine basalts and andesite overlie all other bedrock units (Hoare and Coonrad, 1959; Bundtzen and Laird, 1991).

Unconsolidated fluvial, colluvial, and eolian deposits that range in age from late Tertiary to Holocene cover at least 50 percent of the maturely eroded Kuskokwim Mountains. Pleistocene glaciation was restricted to resistant, igneous-cored upland mountain ranges and locally affected the distribution of heavy mineral placers deposits in the study area.

The dominant deformation affecting rocks of the Kuskokwim mineral belt began in Late Cretaceous time, although earlier deformational events are preserved in preamalgamation, pre-Cretaceous rocks (Patton et al., 1994). The postaccretionary, overlap assemblages were deformed in a right-lateral, wrench fault tectonic environment characterized by en echelon folds and high-angle faults (Miller and Bundtzen, 1994). The oldest overlap assemblages (middle Cretaceous) are the most highly deformed and were subjected to multiple fold episodes characterized by steep subisoclinal folds; the Late Cretaceous and younger rocks are more broadly folded. The wrench fault tectonic environment probably controlled the formation of the Yukon-Koyukuk and Kuskokwim basins and the emplacement of Late Cretaceous-early Tertiary plutonic and volcanic rocks (Miller and Bundtzen, 1992, 1994).

TABLE 2. Selected Gold- and Silver-Bearing Lode Deposits Associated with Late Cretaceous-Early Tertiary Igneous Complexes, Kuskokwim Mineral Belt, Showing Metallic Resource Estimates Where Available

Deposit name	Deposit type	Principal commodities	Mineralization (t)	Gold (kg)	Silver (kg)	Copper (t)	Tin (kg)	References
Chicken Mountain	Plutonic-hosted Cu-Au-polymetallic	Au, Ag, As, Sb, Cu	14,500,000	17,400	—	13,050	—	Bundtzen et al. (1992); V. Hollister, written commun. (1992)
Golden Horn	Plutonic-hosted Cu-Au-polymetallic	Au, As, W, Sb	2,850,000	3,420	9,690	—	—	Bundtzen et al. (1992)
Von Frank Mountain	Plutonic-hosted Cu-Au-polymetallic	Au, Cu	—	—	—	—	—	J. DiMarchi, pers. commun. (1993)
Owhat-Mission Creek	Plutonic-hosted Cu-Au-polymetallic	Au, Ag, Cu, As	229,000	1,030	—	4,589	—	Bundtzen and Laird (1991)
Wattamuse prospect	Plutonic-hosted Cu-Au-polymetallic	Au, Ag	—	—	—	—	—	Hickok (1990b); this study
Ikuk prospect	Plutonic-hosted Cu-Au-polymetallic	Au, Ag	—	—	—	—	—	Hickok (1990a); this study
Nixon Fork	Au-Cu-Bi skarn associated with deposit type above	Au, Ag, Cu, Bi	85,345	4,130	—	1,706	—	Bundtzen et al. (1994)
Candle Hills	Plutonic-hosted Cu-Au-polymetallic	Au, Ag, Cu	—	—	—	—	—	Bundtzen and Laird (1983b); this study
Donlin	Granite-porphyry Au-polymetallic	Au, Ag, Sb	40,370,400	111,960	—	—	—	Retherford and McAtee (1994); Bundtzen et al. (1996); this study
Independence mine	Granite-porphyry Au-polymetallic	Au, Ag, Sb	—	—	—	—	—	Bundtzen and Laird (1983, 1983a); this study
Vinasale Mountain	Granite-porphyry Au-polymetallic	Au, Ag	10,300,000	24,540	—	—	—	DiMarchi (1993); Bundtzen (1986); Swainbank et al. (1995)
Granite and Julian Creeks	Granite-porphyry Au-polymetallic	Au, Ag, Sb	—	—	—	—	—	Bundtzen et al. (1985)
Ophir dike swarm	Granite-porphyry Au-polymetallic	Au, Ag	—	—	—	—	—	Bundtzen and Laird (1980); this study
Arnold-Willow Creek prospect	Granite-porphyry Au-polymetallic	Au, Ag	—	—	—	—	—	Nokleberg et al. (1993); this study
Cirque	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Cu, Ag, Sn	175,000	—	77,875	6,125	—	Bundtzen and Laird (1982); M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun. (1995)
Tolstoi	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Cu, Ag	1,500,000	—	—	—	—	Bundtzen and Laird (1982); M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun. (1995)
Bismarck Creek	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn, Cu, Zn	498,000	—	23,804	797	682,260	This study
Granite Mountain pipe	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn	5,000,000	—	—	—	—	This study
Win	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn	—	—	—	—	—	Burleigh (1992a)
Won	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn	1,937,060	—	89,646	1,821	11,476,080	Burleigh (1992b)
Pupinski	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Cu, Ag, Sn, Zn	—	—	—	—	—	This study
Dishna River	Au-Ag epithermal	Au, Ag, Sb	37,600	92	—	—	—	This study
Kolmakof	Au-Ag epithermal	Hg, Sb, Au, Ag, Te	—	—	—	—	—	Bundtzen et al. (1993); this study
Poison Creek	Au-Ag epithermal	Au, Ag, Hg	—	—	—	—	—	This study
Yetna volcanic field	Au-Ag epithermal	Ag, Au	—	—	—	—	—	This study
Bogus Creek	Au-Ag epithermal	Ag, Au, Sb	—	—	—	—	—	This study
Total	—	—	77,482,405	162,572 (5,227,000 oz)	201,015 (6,464,000 oz)	28,088	12,158,340 (12,160 t)	

The metallic volume estimates summarized in this table represent a range of levels of uncertainty that lumps inferred, proven, and probable resources and reserves

— = resource estimates unavailable

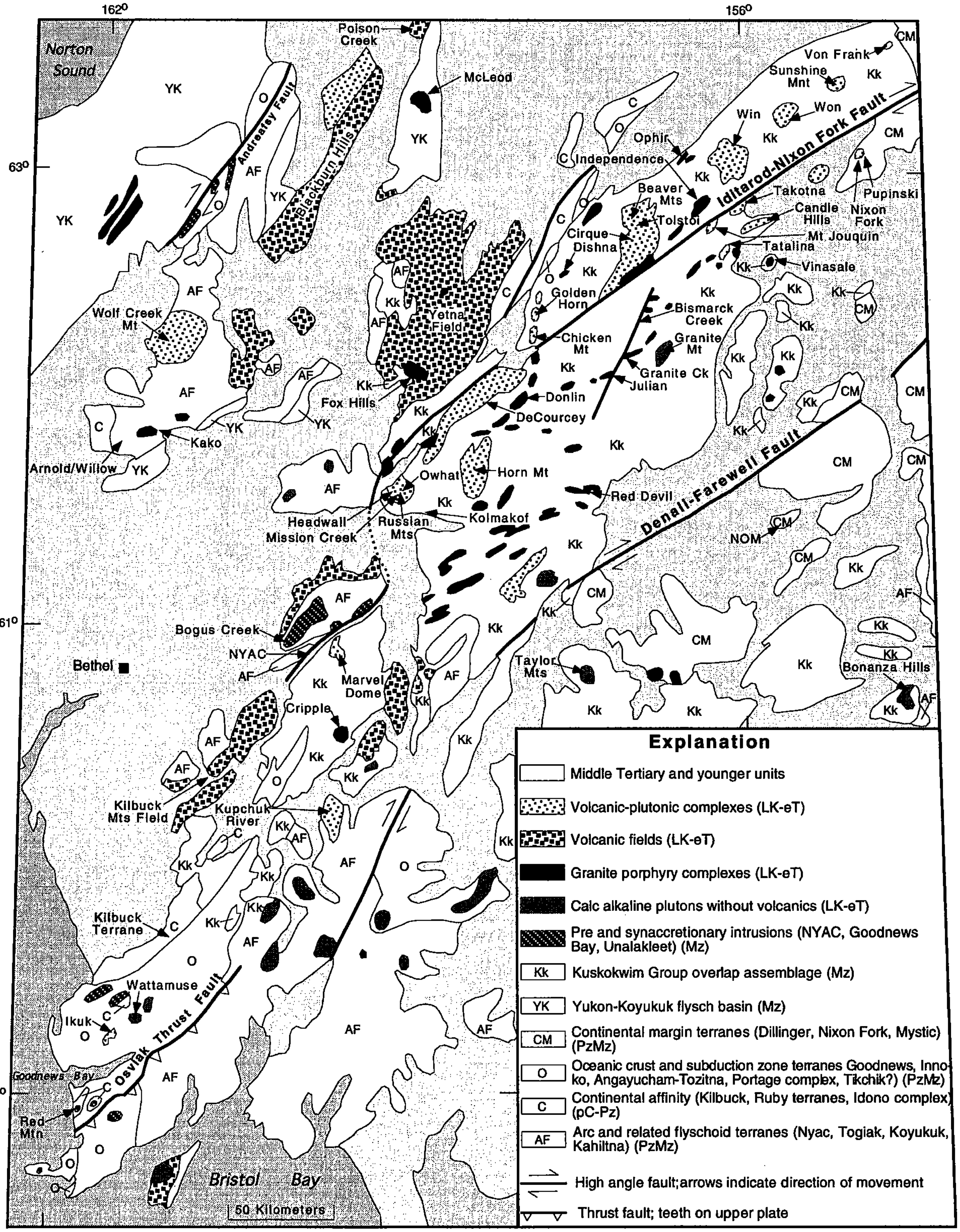


FIG. 2. Regional geology of southwestern Alaska, showing distribution of pre-, syn-, and postaccretionary geologic units, Late Cretaceous-early Tertiary igneous complexes, and names of the significant precious metal-bearing mineral deposits of the Kuskokwim mineral belt that are discussed in this paper. Geologic base from unpublished compilation by M.L. Miller and T.K. Bundtzen (1994).

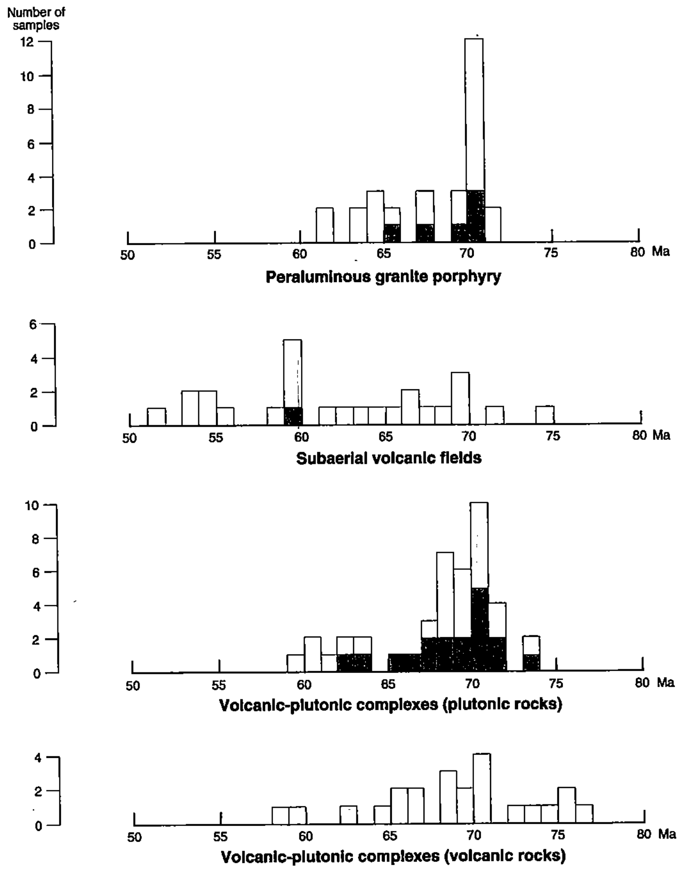


FIG. 3. Histogram summary of selected isotopic age determinations from Late Cretaceous-early Tertiary igneous rocks in the Kuskokwim mineral belt. Shading indicates age from a mineralized system. Most age determinations are by conventional K-Ar method. However, six determinations (four subaerial volcanic rocks and two plutonic rock samples) are by $^{40}Ar/^{39}Ar$ total fusion method, which yielded the same age ranges as the K-Ar analytical method. Data are from Moll et al. (1981), Patton and Moll (1985), Miller et al. (1989), Bundtzen and Laird (1991), Solie et al. (1991), Box et al. (1993), DiMarchi (1993), Miller and Bundtzen (1994), W.W. Patton, Jr., and E.J. Moll-Stalcup (written commun., 1995), and this report.

Description of Late Cretaceous-Early Tertiary Igneous Rocks

Late Cretaceous-early Tertiary igneous rocks of the Kuskokwim mineral belt form a 550-km-long belt of intrusive rocks and volcanic fields extending from Goodnews Bay, on the southwestern coast, northeast to Von Frank Mountain; the belt may continue an additional 220 km to the Cosna River in interior Alaska. These rocks, which range in age from 77 to 52 Ma (Wilson et al., 1994; Fig. 3), intrude and overlie many of the Paleozoic-Mesozoic lithotectonic terranes and both Cretaceous basin fill sequences in southwestern and western Alaska. About 70 percent of the Late Cretaceous-early Tertiary igneous complexes intrude and overlie the Upper Cretaceous Kuskokwim Group. In the following summary, stated K-Ar isotope ages (except minimum ages) contain an analytical error of 2.5 percent; stated $^{40}Ar/^{39}Ar$ isotope ages, an analytical error of approximately 0.5 percent; and fission track ages, an analytical error of about 8 percent.

Volcanic-plutonic complexes

At least a dozen volcanic-plutonic complexes intrude the Kuskokwim Group in the area examined (Fig. 2). The largest and best exposed of these igneous complexes occur in the Beaver Mountains of the north-central Iditarod quadrangle and in the Russian, Horn, Chuilnik, and Kiokluk Mountains of the Sleetmute quadrangle. Other, smaller volcanic-plutonic complexes are found at Twin, Cloudy, Page, and Von Frank Mountains in the Medfra quadrangle; the Candle Hills in the McGrath quadrangle; at Takotna Mountain, Mount Joaquin, Chicken Mountain, and Granite Mountain in the Iditarod quadrangle; at Marvel Dome and Kupchuk River in the Bethel quadrangle; and at Wattamuse and Ikuk in the Goodnews quadrangle (Fig. 2). Geologic mapping has shown that slightly older volcanic rocks are intruded by comagmatic high-level intrusions. The volcanic-plutonic complexes of the Kuskokwim mineral belt range in size from the 650-km^2 Beaver Mountains complex (the largest) to the 8-km^2 Mount Joaquin complex (Fig. 2).

Extrusive sections of the volcanic-plutonic complexes are generally 500 to 1,000 m thick and consist of basal tuffs overlain by andesite and basaltic andesite flows and lesser volcanic agglomerate (Miller and Bundtzen, 1988, 1994; Decker et al., 1995). Recognition of the same volcanic succession on opposite sides of the Iditarod-Nixon Fork fault in the Beaver Mountains and at DeCourcy Mountain, respectively, led Miller and Bundtzen (1988) to estimate that approximately 90 km of right-lateral offset had occurred along the Iditarod-Nixon Fork fault since Late Cretaceous time. This offset volcanic section forms the Iditarod Volcanics and ranges in age from 76 to 58 Ma; 23 isotopic ages average 68.3 Ma (Fig. 3). Volcanic components of the Chuilnik and Kiokluk Mountains volcanic-plutonic complexes south of Sleetmute (Figs. 1, 2) have yielded a similar age range of 75 to 64 Ma (Reifenstuhl et al., 1984; Miller et al., 1989; Decker et al., 1995). Volcanic components of the Horn Mountains (Sleetmute quadrangle) and Russian Mountains (Russian Mission quadrangle) volcanic-plutonic complexes have, to date, yielded only Late Cretaceous isotopic ages (Bundtzen and Laird, 1991; Bundtzen et al., 1993).

Plutonic rocks associated with the volcanic-plutonic complexes range in composition from alkali gabbro to granite, but monzonite and quartz syenite are the most common compositions in the intrusions. Concentric mineral reaction rims, for example, olivine-clinopyroxene-orthopyroxene-biotite (amphibole), are commonly observed in thin section; these textural relationships indicate that a well-developed differentiation process occurs in intrusions of the volcanic-plutonic complexes (Bundtzen et al., 1992). Most of the volcanic-plutonic complexes intrude the Kuskokwim Group, but a few intrude the Yukon-Koyukuk basin fill sequence and some of the older lithotectonic terranes. Hornfels aureoles as wide as 2 km surround the larger plutons, and in some areas, the occurrence of sandstone hornfels indicates the presence of a buried pluton at depth. K-Ar and $^{40}Ar/^{39}Ar$ data from the plutons indicate a bimodal distribution of ages: one group ranges from 64 to 61 Ma, the other from 71 to 66 Ma. The latter group predominates; 42 isotopic ages from both populations average 67.7 Ma (Fig. 3).

Calc-alkaline plutons without volcanic rocks

Plutons ranging in composition from diorite to granite intrude pre-Tertiary rocks throughout the Kuskokwim mineral belt. They range in composition from diorite to granite and exhibit the same age range and mineralogy as intrusions of the volcanic-plutonic complexes; however, the calc-alkaline plutons lack overlying volcanic stratigraphy. The largest plutons include those in the Taylor Mountains and Bonanza Hills (Fig. 2). K-Ar isotope ages range from 70 to 62 Ma, or about the same as those for plutons in volcanic-plutonic complexes; 12 isotopic ages average 68.1 Ma. Because of similarities in age and composition, this plutonic suite has been combined with plutons of volcanic-plutonic complexes in Figure 3.

Subaerial volcanic rocks

Subaerial volcanic rocks—generally without plutonic equivalents—form extensive fields that overlie older preaccretionary terranes in the Yetna River drainage (Iditarod and Holy Cross quadrangles), in the Blackburn Hills area (Unalakleet and Holy Cross quadrangles), at Wolf Creek Mountain (Holy Cross quadrangle), at Poison Creek north of Anvik (Unalakleet quadrangle), and along the northern flanks of the Kilbuck Mountains (Bethel and Russian Mission quadrangles). These volcanic fields range from 80 km^2 at Wolf Creek Mountain to about 5,000 km^2 in the Yetna River area, which makes them the most aerially extensive of the Late Cretaceous-early Tertiary igneous suites. K-Ar ages range from 74 to 52 Ma; 26 isotopic ages average 62.5 Ma, making them slightly younger than the extrusive components of the volcanic-plutonic complexes (Fig. 3). These volcanic fields locally contain thick accumulations of ash-flow tuffs in addition to more typical andesitic volcanic flows. Small felsic intrusions are associated with the Wolf Creek Mountain and Blackburn Hills fields, but otherwise they exhibit petrographic and geochemical features similar to those of the other subaerial volcanic centers. Results of 35 major oxide analyses—25 from the Yetna volcanic field (Miller and Bundtzen, 1994), six from the Kilbuck Mountains (Box et al., 1993), and four from Wolf Creek Mountain (T.K. Bundtzen and M.L. Miller, unpub. data)—suggest broad calc-alkaline trends similar to the volcanic-plutonic complexes. A genetic relationship between magma sources of the volcanic-plutonic complexes and the subaerial volcanic fields is indicated, despite some differences in the average ages of the two suites.

Peraluminous granite-porphyry dikes, stocks, and sills

Peraluminous granite-porphyry dikes, stocks, and sills are volumetrically minor but form important and distinct rocks in the study area. The dominant composition is granite or alkali quartz granite; however, minor amounts of granodiorite and quartz monzodiorite also exist in the suite (Fig. 4). These intrusions are peraluminous and corundum normative and commonly contain garnet phenocrysts. Available K-Ar and $^{40}Ar/^{39}Ar$ analyses range from 71 to 61 Ma; 29 isotopic ages average 67.5 Ma (Fig. 3). The granite-porphyry bodies occur in elongate belts almost certainly controlled by northeast-trending, high-angle, regional faults. Individual sills or dikes rarely cover more than 2 or 3 km^2. A majority of the granite-porphyry dikes, sills, and small plutons occur in the central and northern portions of the Kuskokwim mineral belt and might be spatially related to the larger volcanic-plutonic complexes and transcurrent faults (Fig. 2). However, small intrusions of this type probably occur throughout the study area.

Petrogenesis of Late Cretaceous-early Tertiary igneous rocks

The volcanic-plutonic complexes and the subaerial volcanic rocks are probably genetically related, as suggested by their common spatial association, and supported by similar chemistry and isotopic ages (Bundtzen et al., 1992; Szumigala, 1993; Miller and Bundtzen, 1994; Moll-Stalcup, 1994). When plotted on the normative QAPF (Q = silica minerals, A = alkali feldspars, including albite, P = plagioclase, F = feldspathoid minerals) diagram of Streckeisen and LeMaître (1979), compositions of mineralized plutons rocks range from diorite to alkali granite (Fig. 4). Based on the alkali-lime index of Peacock (1931), most of the volcanic and plutonic rocks from mineralized systems in the Kuskokwim mineral belt exhibit alkali-calcic affinities (Fig. 5), which is supported by petrographic data as well.

Figure 3 summarizes 120 isotopic age determinations from selected Late Cretaceous-early Tertiary igneous rocks in the Kuskokwim mineral belt. Shaded areas depict igneous ages from mineralized complexes. Most of the isotopic age dates are K-Ar mineral and whole-rock ages; however, six determinations are $^{40}Ar/^{39}Ar$ total fusion dates, which yielded the same ages as those determined by the K-Ar analytical method. On the basis of regional geology, structural deformation, igneous petrographic studies, and the isotopic age results, we believe that most plutonic and volcanic rocks in the Kuskokwim mineral belt underwent simple thermal histories. Hence the older K-Ar age determinations summarized in Figure 3 are believed to be accurate representations of crystallization ages of the four igneous suites.

Rb-Sr isotope data from six mineralized volcanic-plutonic igneous suites in the study area exhibit $^{87}Sr/^{86}Sr$ initial ratios ranging from 0.70472 to 0.70585, suggesting that the Late Cretaceous-early Tertiary volcanic fields and volcanic-plutonic complexes from the Kuskokwim mineral belt are mantle derived, which is also consistent with their origins in a subduction-related environment (Table 3).

Although similar in age to other Late Cretaceous-early Tertiary igneous rocks, the granite-porphyry suite is chemically distinct. The rocks are peraluminous, corundum normative, and locally contain garnet phenocrysts, suggesting derivation from melted continental crust (Miller and Bundtzen, 1994). Limited REE data (Bundtzen et al., 1992) indicate that the granite-porphyry in the Kuskokwim mineral belt is substantially depleted in heavy rare earth elements, whereas the other types of volcanic and plutonic rocks in the Kuskokwim mineral belt are not. Geochemical evidence (high aluminum content) and mineralogical evidence (garnet phenocrysts) suggest that the granite-porphyry dikes and sills may involve partial melting of continental crust brought about by high heat flow generated during emplacement of the volcanic-plutonic complexes previously described.

Major oxide data from 13 gold-bearing plutons in the Kuskokwim mineral belt were plotted on an alkalinity versus ferric/ferrous oxide ratio diagram, as advocated by Leveille

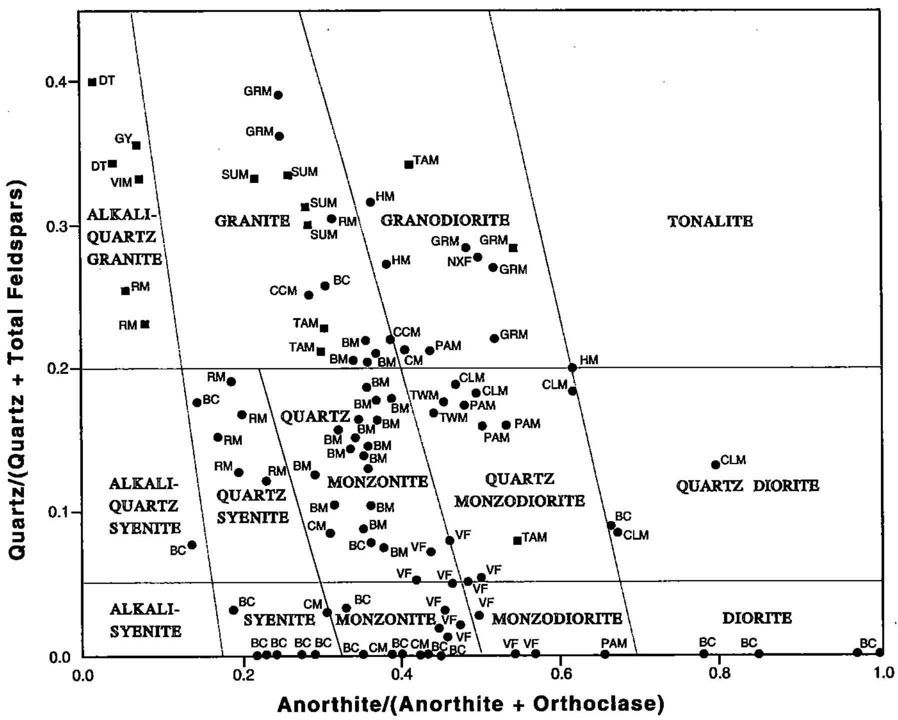


FIG. 4. Normative QAPF diagram, after Streckeisen and LeMaître (1979), of selected Late Cretaceous-early Tertiary plutonic rocks associated with gold-silver mineralization from the Kuskokwim mineral belt of southwest Alaska. Data from Moll et al. (1981), Bundtzen and Laird (1983b, 1991), Bull (1988), Bundtzen et al. (1992), Bundtzen et al. (1993), DiMarchi (1993), Szumigala (1993), and Miller and Bundtzen (1994). Abbreviations of plutons: BC = Black Creek Stock, BM = Beaver Mountains, CCM = Cripple Mountains, CLM = Cloudy Mountain, CM = Chicken Mountain, DT = Donlin Trend, GRM = Granite Mountain, GY = Ganes-Yankee Creek, HM = Horn Mountains, NXF = Nixon Fork, PAM = Page Mountain, RM = Russian Mountains, SUM = Sunshine Mountains, TAM = Talida Mountains, TWM = Twin Mountain, VF = Von Frank Mountain, VIM = Vinasale Mountain. Squares denote plutons associated with peraluminous granite-porphyry gold polymetallic deposits. Circles denote plutons associated with plutonic-hosted copper-gold polymetallic stockwork and vein deposits, and plutonic-related, boron-enriched silver-tin polymetallic systems.

et al. (1988) for determining gold favorability. Keith and Swan (1987) first suggested that the oxidation state of a pluton influences its gold-bearing potential and concluded that a low oxidation state indicated gold-favorable conditions. Mishin and Petukhora (1990) have used a similar method to determine gold favorability in mineralized Cretaceous to Tertiary plutons of the Okhotsk-Chukotka igneous belt of the Russian northeast. The alkalinity index used in Figure 6 is one modified from Mutschler et al. (1985) after Macdonald and Katsura (1964). Analyses that plot above zero on the y axis are considered alkaline, whereas those that plot below it are considered subalkaline. Plutonic oxidation state is determined by the whole-rock Fe_2O_3/FeO ratio, which is an approximation of oxygen fugacity. Leveille et al. (1988) plotted over 630 whole-rock analyses on an alkalinity versus ferric/ferrous oxide ratio diagram, using examples of both gold-bearing and nongold-bearing plutons throughout the western United States and Alaska. These workers argued that magnetite-rich magmas result in a decrease in gold concentration in the residual liquids during increasing differentiation of the cooling intrusive body. Furthermore, in order for a magma containing little magnetite to crystallize, it must have a low oxygen fugacity, a high K feldspar content, or some combination of both. According to Leveille et al. (1988), the influence of the oxidation state of the hydrothermal system may be of considerable importance, because reduced plutons will buffer a hydrothermal system to oxidation states favorable for gold deposition from a bisulfide complex.

Figure 6 shows that all but one of the plutons from mineralized volcanic-plutonic complexes in the Kuskokwim mineral belt plot in the gold-favorable field. In contrast, however, samples from gold-bearing, peraluminous granite-porphyry at Donlin Creek, Vinasale Mountain, and the Ganes-Yankee Creek dike swarm plot mainly in the unfavorable field, even though these oxidized, granite-porphyry intrusions contain significant gold mineralization. Hence the alkalinity versus ferric/ferrous ratio is apparently a good predictive tool for gold favorability in volcanic-plutonic complexes but does not reliably predict the presence of gold in the peraluminous granite-porphyry suite (Fig. 6). Leveille et al. (1988) determined that whole-rock analyses from plutons in gold-bearing, base metal porphyry systems did not always plot in the gold-favorable field on an alkalinity versus ferric/ferrous oxide ratio diagram; they concluded that pervasive, sometimes subtle alteration and oxidation render their application to this method questionable. This may also be the case for predicting gold favorability in the granite-porphyry suite described in this paper.

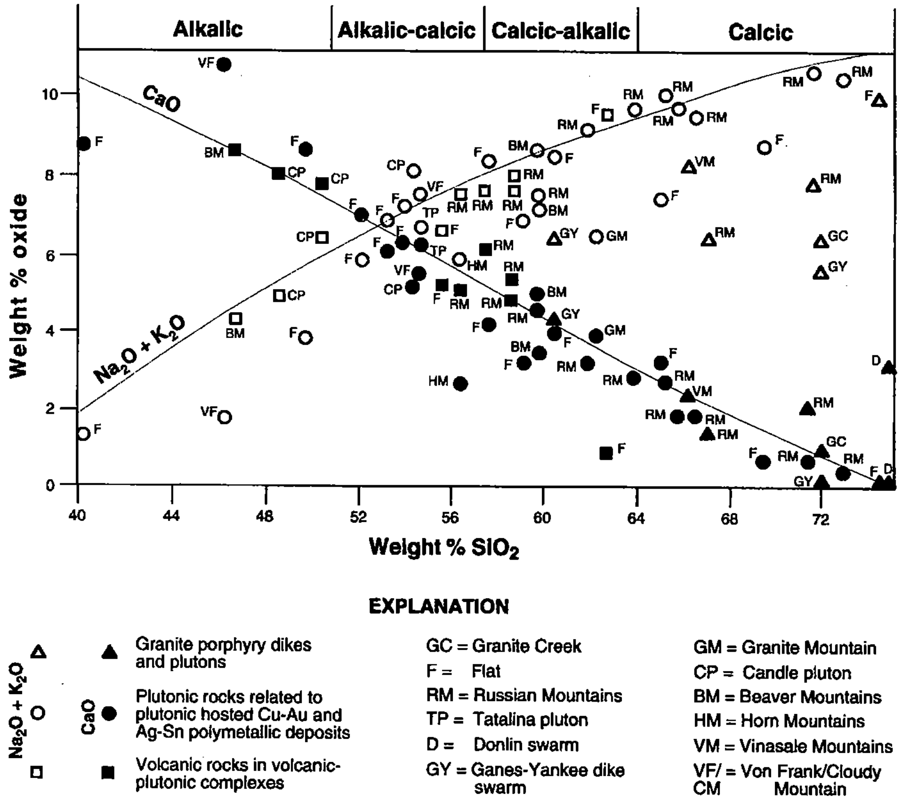


FIG. 5. Classification of volcanic and plutonic rocks from selected mineralized Late Cretaceous-early Tertiary igneous complexes in the Kuskokwim mineral belt, using the alkali-lime index of Peacock (1931). Volcanic-plutonic complexes generally plot in the alkali-calcic field; granite-porphyry complexes show a wide scatter of data points. Data from Moll et al. (1981), Bundtzen and Laird (1983b), Bundtzen et al. (1992), Bundtzen et al. (1993), Miller and Bundtzen (1994), and authors (unpub. data).

Economic Geology

Classification scheme for Late Cretaceous-early Tertiary metallogeny

Mineral deposits associated with igneous rocks of the Kuskokwim mineral belt are characterized by their alteration, metal content, mineralogy, detailed geologic setting, age, and trace element and isotopic data. Five major groups of mineral deposit types are summarized in this paper: (1) plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits, (2) peraluminous granite-porphyry-hosted gold polymetallic deposits, (3) plutonic-related, boron-enriched silver-tin polymetallic mineralization in breccia pipes and as replacement deposits, (4) gold and silver mineralization associated with epithermal systems, and (5) gold polymetallic heavy mineral placer deposits. Table 2 lists the major precious metal-bearing deposits of the Kuskokwim mineral belt, divides them by deposit type, lists principal commodities present in each deposit, and provides resource grade and size estimates where available. None of the deposits has been completely explored.

Other mineral deposits associated with the Late Creta-

TABLE 3. Rb-Sr Isotope Data from Selected Late Cretaceous-Early Tertiary Igneous Complexes in the Kuskokwim Mineral Belt

Field no.	Rocky type	Locality[1]	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ (initial)[2]
78BT435	Monzonite	Mount Joaquin	115	580	0.574	0.70556	0.70499
78BT461	Monzodiorite	Takotna	141	475	0.858	0.70611	0.70526
78BT379	Monzonite	Candle Hills	138	541	0.736	0.70658	0.70585
82BT431	Alkali gabbro	Golden Horn-Black Creek	155	619	0.725	0.70544	0.70472
81BT524	Basalt	Beaver Mountains	236	631	1.082	0.70613	0.70505
77BT234	Basalt	Candle Hills	106	518	0.591	0.70712	0.70653

Analyses by Teledyne Isotopes, Westwood, New Jersey; Accuracy of concentration data is ± 1%, determined through repeated analyses of well-characterized reference materials; precision of $^{87}Sr/^{86}Sr$ (initial) is generated from each mass spectrum run

[1] Localities in Figure 2

[2] Calculated using -1.42×10^{-10} yr^{-1} and age = 70 Ma

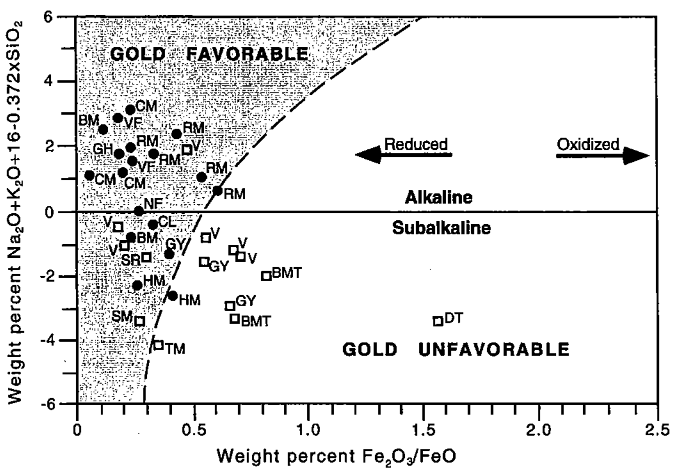


FIG. 6. Plot of gold favorability, utilizing alkalinity versus ferric/ferrous ratio, as advocated by Leveille et al. (1988), from 13 gold-bearing plutons in the Kuskokwim mineral belt. Identification and data sources are as follows: BM = Beaver Mountains (Bundtzen and Laird, 1982; Szumigala, 1993); BMT = Barometer Mountain (unpub. data, this study), CL = Cloudy Mountain (Moll et al., 1981); CM = Chicken Mountain (Bundtzen et al., 1992); DT = Donlin trend (Bundtzen et al., 1993); GH = Golden Horn (Bundtzen et al., 1992); GY = Ganes-Yankee Creek complex (unpub. data, this study); HM = Horn Mountains (Bundtzen et al., 1993); NF = Nixon Fork (Moll et al., 1981; unpub. data, this study); RM = Russian Mountains (Bundtzen and Laird, 1991); SM = Sunshine Mountain (Moll et al., 1981); SR = Sulokna stock (Moll et al., 1981); TM = Telida Mountain (Moll et al., 1981); V = Vinasale (DiMarchi, 1993; unpub. data, this study); VF = Von Frank Mountain (Moll et al., 1981). Circles denote (1) plutons associated with plutonic-hosted copper-gold polymetallic stockwork and vein deposits; and (2) plutonic-related, boron-enriched silver-tin polymetallic systems. Squares denote plutons associated with peraluminous granite-porphyry-hosted gold polymetallic deposits.

ceous-early Tertiary igneous rocks of the Kuskokwim mineral belt include (1) molybdenum porphyry prospects at Fox Hills, Molybdenum Mountain, and McLeod (Nokleberg et al., 1995), (2) REE mineralization associated with felsic volcanic calderas and plutons in the Sischu volcanic field and at Wolf Creek Mountain, and (3) more than a dozen, past-producing, structurally controlled mercury-antimony deposits in flysch, which include the DeCourcy Mountain, Barometer, Cinnabar Creek, Mountain Top, and Red Devil mines (Sainsbury and MacKevett, 1965). These three metallic deposit types are not described in detail in this paper. Gray et al. (1997) describe mercury-antimony systems in the study area. Nokleberg et al. (1987, 1993) and Bundtzen and Koch (1993) provide compilations of significant placer and lode mineral deposits of Alaska, which include selected mineral deposits in the Kuskokwim mineral belt.

Table 4 presents average elemental content of 20 representative precious metal-bearing deposits in the Kuskokwim mineral belt. Figure 7 provides photographs of mineralized samples that illustrate megascopic textures and sulfide, sulfosalt, oxide, and alteration mineralogy of precious metal deposits in the study area. Figure 8 provides photomicrographs that illustrate selected paragenetic relationships between sulfide and sulfosalt minerals. These figures and tables are frequently referred to in discussion of the four mineral deposit types below. During our discussion of igneous rocks, unless otherwise referenced, the principal classification schemes used are Streckeisen and LeMaître (1979) for plutonic rocks and Irvine and Baragar (1971) for volcanic rocks.

Plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits

Plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits are found in at least eight volcanic-plutonic complexes in the Kuskokwim mineral belt. All eight examples described here—Chicken Mountain, Golden Horn, Von Frank Mountain, Candle Hills, Nixon Fork, Owhat-Mission Creek, and the Wattamuse and Ikuk prospects—contain many attributes of disseminated, bulk tonnage gold deposits. Quartz sulfide stockwork occurs in the Chicken Mountain, Golden Horn, and Von Frank Mountain deposits but is not as well recognized in the Owhat-Mission Creek, Wattamuse, and Ikuk prospects or in the Candle Hills and Nixon Fork plutons.

Alteration types, where recognized, include biotite + K feldspar or sericite + quartz + dolomite + ankerite in plutonic centers (protore) and a weakly developed propylitic (chlorite-iron oxide) alteration distal from intrusive centers. Early base metal-rich sulfide veins contain strong ankerite alteration; gold-bearing veins usually contain dolomite and chlorite alteration. Late-forming veins generally exhibit argillic and silicic alteration zones. Secondary metallic enrichment or supergene zones are absent in all deposits examined, and surface iron staining is only weakly developed.

Samples of mineralization from four sulfide quartz depositional events in the Chicken Mountain and Golden Horn lodes contain both liquid-rich and solid-bearing inclusions that exhibit at least one gas phase; all inclusions are generally NaCl poor (1.8–5.5 wt %) and contain 70 to 80 percent H_2O (Bundtzen et al., 1992; Table 5, this study).

Silver to gold ratios from five representative plutonic-hosted copper-gold polymetallic deposits in the study area range from 0.6:1 to 6.3:1 and average 3.3:1 (Table 4). Principal metals present are copper, gold, silver, arsenic, and antimony. Moderately elevated levels of lead, tungsten, bismuth, uranium, thorium, and molybdenum locally occur in these deposits (Table 4). One deposit (Chicken Mountain) contains anomalous tantalum in zones developed during an early deuteric-magmatic mineralizing event.

All of the plutons that host these mineral deposits range in age from 66 to 71 Ma. Most intrude Kuskokwim Group flysch, a few intrude the Goodnews terrane, and one intrudes the Nixon Fork terrane (Fig. 2). The best examples of the plutonic-hosted copper-gold polymetallic deposit type generally occur in complex multiphased plutons that contain alkaline compositional phases such as alkali gabbro or monzodiorite.

The geology, structure, mineralogy, metallic content, and alteration found in most plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits of the study area generally conform to the alkalic porphyry copper-gold model of Lowell and Guilbert (1970) or to deposit models 20c (porphyry Cu-Au; Cox, 1986b), 18b (Cu skarn; Cox and Theodore, 1986), and 22c (polymetallic veins; Cox, 1986a), respectively. The plutonic-hosted copper-gold polymetallic deposits contain an estimated 25,980 kg of gold, or 16 percent of the known gold resources in the Kuskokwim mineral belt.

TABLE 4. Average Elemental Content of 20 Representative Precious Metal-Bearing, Hard-Rock Mineral Deposits of Late Cretaceous-Early Tertiary Age in the Kuskokwim Mineral Belt of Southwest Alaska

	Au	Ag	As	Sb	Hg	Cu	Pb	Zn	Bi	Cr	U	Th	Mo	Nb	Sn	W	Co	Ni	No. of samples analyzed[1]	References
Plutonic-hosted copper-gold-polymetallic deposits																				
Chicken Mountain	1.20	4.6	617	53	1.56	490	17	46	1.0	165	4.5	8.0	65	31.0	7	5	28	99	98	Bundtzen et al. (1992); this study; Richard Gosse, written comm. (1990)
Golden Horn	9.90	21.8	19,000	12,000	2.96	343	210	75	2.0	304	3.0	8.5	3	29.0	ND	20,000	11	45	47	Bundtzen et al. (1992); this study
Russian Mountain Lodes	4.50	28.0	95,900	2,000	ND	8,700	1,042	287	93.0	281	12.4	9.1	1.8	34.0	22	22	170	125	51	Bundtzen and Laird (1991); this study
Candle	0.80	2.9	—	ND	—	299	59	78	ND	20	8.9	23.2	ND	ND	ND	ND	8	100	15	Bundtzen and Laird (1983b); this study
Nixon Fork-Mystery	164.70	95.0	5,150	653	—	42,098	1,763	—	1,217.0	51	ND	ND	17.0	1.5	13	ND	49	25	5	This study
Peraluminous granite-porphyry-hosted gold-polymetallic deposits																				
Donlin	3.20	2.7	664	3,500	2.38	105	69	43	ND	138	—	ND	ND	ND	9	2	21	28	24	McGimsey et al. (1988); this study
Ganes-Yankee Creek	1.85	2.0	2,214	ND	0.18	42	146	38	3.7	389	—	ND	ND	ND	43	ND	28	68	16	Bundtzen and Laird (1980); McGimsey et al. (1988)
Ophir	0.23	2.3	1,845	ND	—	84	5	ND	ND	129	3.1	8.9	ND	ND	ND	5	ND	67	20	Bundtzen and Laird (1980); this study
Granite Creek	0.65	3.1	44	24,308	0.10	12	11	50	ND	53	—	ND	ND	ND	1.0	ND	6	28	42	Bundtzen et al. (1985); McGimsey et al. (1988)
Plutonic-related, boron-enriched silver-tin-polymetallic deposits																				
Cirque	0.22	516.0	718	1,327	0.31	41,369	5,123	621	233.0	45	7.9	18.3	1.0	1.0	780	9	27	15	16	Bundtzen and Laird (1982); McGimsey et al. (1988); this study
Tolstoi	0.43	149.2	2,527	130	ND	3,481	699	1,578	10.0	192	3.8	12.3	3.5	80.0	29	ND	23	48	13	Bundtzen and Laird (1982); McGimsey et al. (1988)
Bismarck Creek	ND	16.4	403	79	0.07	155	183	2,674	3.8	83	4.9	5.3	2.0	5.0	1,370	73	7	49	65	This study; McGimsey et al. (1988)
Granite Mountain	ND	0.9	42	ND	0.04	15	92	236	15.4	247	—	ND	ND	ND	60	ND	18	59	11	McGimsey et al. (1988); this study
Pupinski	0.04	261.0	965	100	—	45,750	104	1,099	ND	154	ND	—	2.0	1.0	36	535	20	23	5	This study; Richard Flander, written commun. (1995)
Won	ND	42.0	4,277	396	—	470	919	1,101	—	—	—	—	—	—	5,930	135	—	—	18	Burleigh (1992b)
Win	ND	388.0	10,810	1,743	—	687	2,656	622	159.0	—	—	—	—	373.0	51,660	—	—	—	20	Burleigh (1992a)
Epithermal gold-silver deposits																				
Kolmakof	1.02	3.6	17	6,500	>50.00	35	15	46	0.2	312	1.5	4.0	ND	15	ND	2	26	48	13	Bundtzen et al. (1993); this study
Glenn Gulch	2.88	155.9	1,296	75,437	2.82	343	176	74	8.1	183	—	7.6	ND	ND	3	20	5	7	9	Bundtzen et al. (1992)
Dishna River	1.82	0.1	4,762	4,888	4.10	15	ND	35	ND	69	—	ND	ND	ND	ND	ND	10	43	16	McGimsey et al. (1988)
Bogus Creek	0.58	107.3	87	38	2.19	76	172	97	ND	17	ND	ND	1.0	ND	10	ND	5	7	9	This study

Data derived from reference cited and this study; analytical methods described in the references; Au, Ag, As, and Sb were analyzed by fire assay techniques; other elements by atomic absorption spectrophotometry, neutron activation, and emission spectrophotometry techniques; because representative values were sought, only deposits with five or more analyses were included in this table; the average metal contents presented do not necessarily constitute the average grade of mineral reserves present in the deposits

All values in ppm; ND = below limits of detection; — = not analyzed

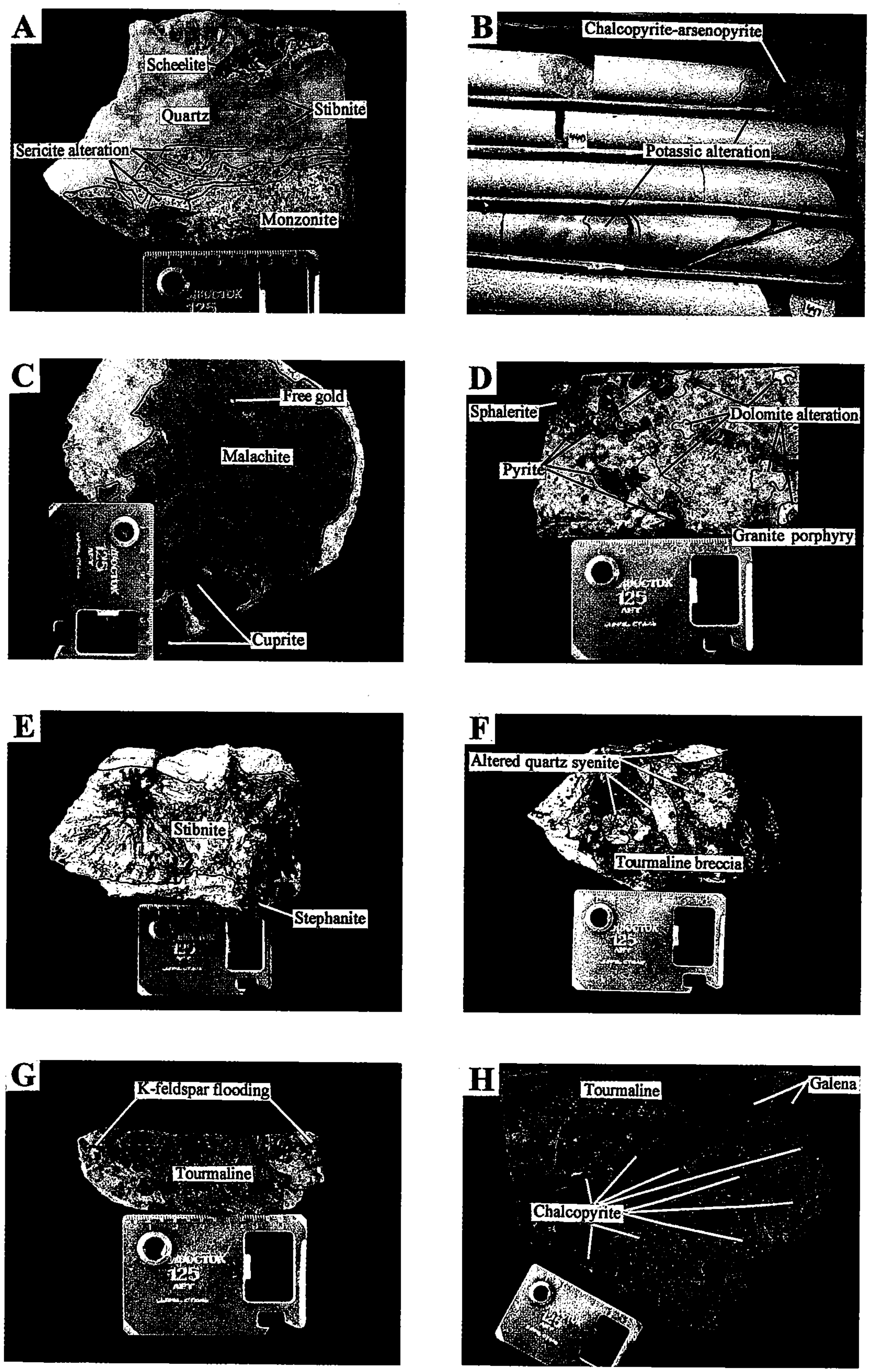

A
Scheelite
Quartz
Stibnite
Sericite alteration
Monzonite
B
Chalcopyrite-arsenopyrite
Potassic alteration
C
Free gold
Malachite
Cuprite
D
Sphalerite
Dolomite alteration
Pyrite
Granite porphyry
E
Stibnite
Stephanite
F
Altered quartz syenite
Tourmaline breccia
G
K-feldspar flooding
Tourmaline
H
Tourmaline
Galena
Chalcopyrite

FIG. 7.

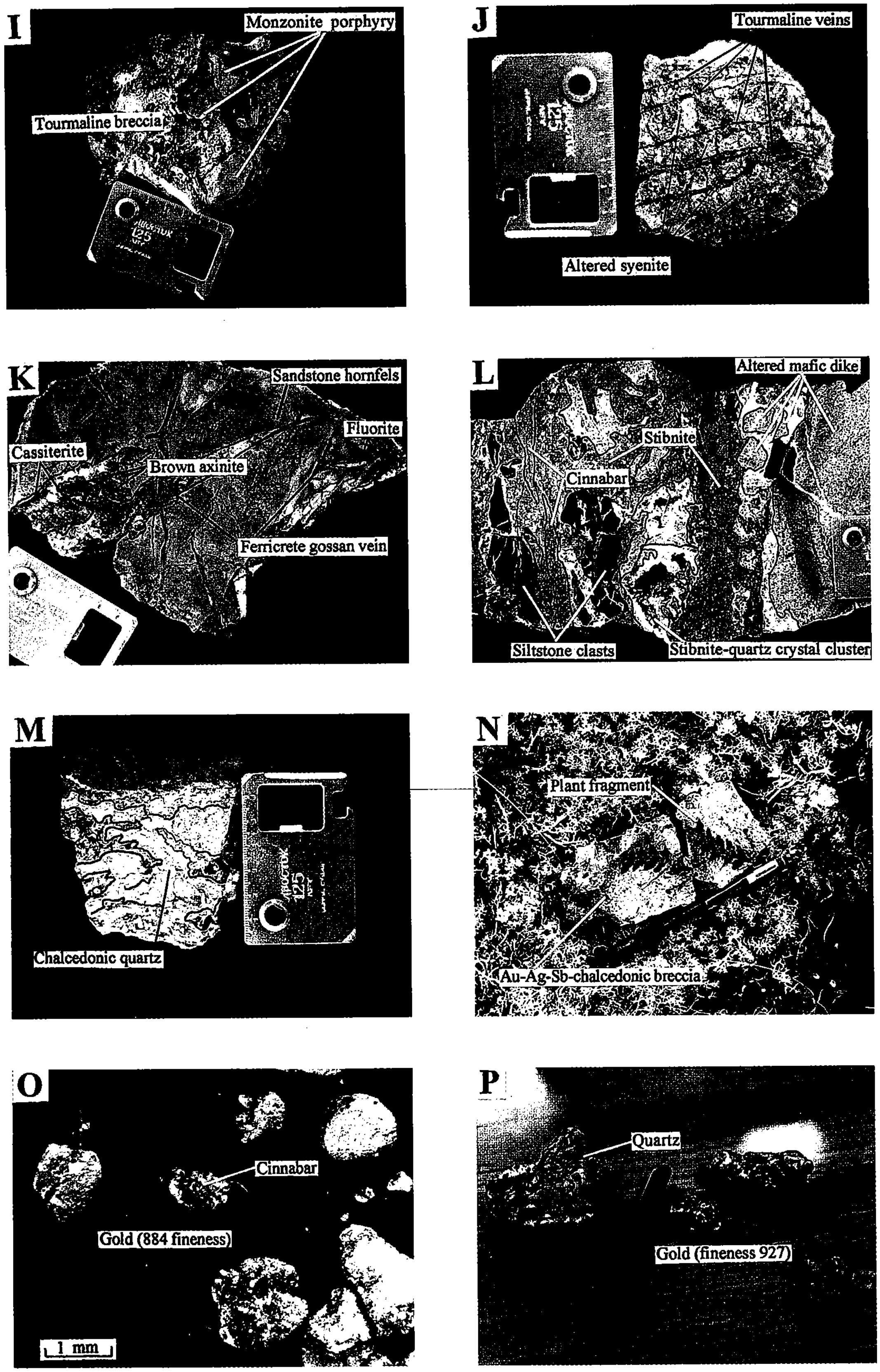

I
Monzonite porphyry
Tourmaline breccia
J
Tourmaline veins
Altered syenite
K
Sandstone hornfels
Fluorite
Cassiterite
Brown axinite
Ferricrete gossan vein
L
Altered mafic dike
Stibnite
Cinnabar
Siltstone clasts
Stibnite-quartz crystal cluster
M
Chalcedonic quartz
N
Plant fragment
Au-Ag-Sb-chalcedonic breccia
O
Cinnabar
Gold (884 fineness)
1 mm
P
Quartz
Gold (fineness 927)

FIG. 7. (*Cont.*)

The Chicken Mountain and Golden Horn gold polymetallic deposits of the Iditarod district have been described in detail by Bundtzen et al. (1992) and Bull (1988) and contain stockwork and vein-fault types of gold ± quartz sulfide deposits that occur in the cupola portions of both the Chicken Mountain and Black Creek plutons (Fig. 9). Almost all of the 45,095 kg (1.45 million oz) of past placer gold production recorded in the Flat area was derived from the erosion of these two mineralized zones. About 84 kg (2,706 oz) of gold and 81 kg (2,620 oz) of silver were recovered from 528 t of high-grade vein-type ore at the Golden Horn deposit.

The Chicken Mountain pluton consists of older alkali gabbro, monzodiorite, and wehrlite that were intruded by an inner phase consisting of monzonite, syenite, and quartz monzonite (Bull and Bundtzen, 1987; Bundtzen et al., 1992). In both the Chicken Mountain and Golden Horn mineralized areas, dumbbell-shaped alteration zones of sericite (core) and ankerite (rim) enclose most of the significant mineralization discovered thus far. Large zones of dolomite replacement formed synchronously with an assemblage consisting of arsenopyrite, pyrite, stibnite, cinnabar, scheelite, chalcopyrite, molybdenite, sulfosalts (owyheeite, acanthite, stromeyerite), and arsenopyrite (Fig. 7A). Sulfide minerals rarely account for more than 5 percent by volume of the total veins and stockwork. Individual veins typically average 1 to 2 cm in width and continue for 10 to 15 m of strike.

Using mineral assemblage paragenesis, alteration, and fluid inclusion data, Bundtzen et al. (1992) described a sequence of mineralization and alteration stages in the Iditarod-Flat district lodes that progressed as follows: (1) a deuteric-magmatic event consisting of muscovite-biotite-quartz (ilmenorutile), en echelon veinlets cutting monzodiorite, and alkali gabbro, (2) extensive sericite-ankerite-quartz and minor chromephengite alteration, mainly as veinlets or replacements in all plutonic phases; accompanied by black sulfide-supported breccias and minor chalcopyrite-molybdenite-quartz stockwork in monzonite-porphyry (Fig. 7B), (3) arsenopyrite-scheelite-gold-quartz veins and stockwork accompanied by extensive chlorite alteration; dolomite breccia veins introduced synchronously with open-space sulfide deposition (Figs. 7A, 8B, C), (4) lead-antimony sulfosalt-gold-owyheeite-stromeyerite-acanthite introduced in shears and faults in quartz monzonite, and (5) quartz-stibnite-gold (cinnabar) in veins in quartz monzonite and quartz syenite sometimes indistinguishable from stage 4 above (Fig. 8H).

Recent subsurface exploration of the Chicken Mountain deposit suggests a drill-indicated reserve of 14.5 Mt grading 1.2 g/t gold, 4.6 g/t silver, 0.09 percent copper, and 0.46 percent antimony to a depth of about 200 m (R. Gosse, written commun., 1990; V. Hollister, written commun., 1992). Bundtzen et al. (1992) estimated that the nearby Golden Horn deposit contains a minimum inferred reserve amounting to 2.85 Mt grading 1.2 g/t gold and 3.4 g/t silver and containing credits of tungsten and antimony (Table 2). Tungsten in the mineral form scheelite is quite abundant in the Golden Horn vein system, but the existing database is insufficient to estimate a tungsten resource. Monzodiorite from the Chicken Mountain pluton yielded hornblende and biotite K-Ar ages of 68.7 and 70.9 Ma, respectively (Bundtzen et al., 1992). Fine-grained, secondary(?) biotite yielded a K-Ar age of 63.4 Ma, which is believed to date hydrothermal mineralization associated with the Golden Horn deposit.

Stockwork-type, copper-gold-bearing mineralization is hosted in quartz diorite and augite-rich biotite granodiorite along a downdropped structural block at the Von Frank Mountain volcanic-plutonic complex about 100 km northeast of McGrath (Figs. 1, 2). The stockwork consists of chalcopyrite, arsenopyrite, minor molybdenite, and free gold in quartz-carbonate veins in a cupola position of the intrusion (J. DiMarchi, oral commun., 1993). Alteration types include sericite, silica, and dolomite replacement zones similar to those observed in the Chicken Mountain plutonic system (Bundtzen et al., 1992). Unmineralized plutonic rocks of the Von Frank pluton (about 3 km north of the prospect) yielded a K-Ar biotite age of 69.9 Ma (Moll et al., 1981).

Copper-gold-silver-arsenic-bearing mineralized zones occur in the Candle Hills volcanic-plutonic complex about 15 km west-southwest of McGrath (Fig. 2). Mineralized zones occur in both volcanic and plutonic rocks and in a small but rich placer gold deposit that produced 4,011 kg (129,000 oz) of gold, formed as a result of the erosion of mineralized zones in the plutonic rocks exposed in Candle Creek (Bundtzen

FIG. 7. Photographs of selected mineralized samples that illustrate megascopic textures and sulfide, sulfosalt, oxide, and alteration mineralogy in mineral deposits of the Kuskokwim mineral belt. A. Auriferous stockwork mineralization in monzonite at Golden Horn, a plutonic-hosted copper-gold polymetallic deposit. B. Drill core showing arsenopyrite-stibnite-sphalerite vein in altered syenite-porphyry of Chicken Mountain, a plutonic-hosted copper-gold polymetallic deposit. C. High-grade, oxidized gold-copper-bismuth ores at Nixon Fork metasomatic deposits adjacent to the Nixon Fork monzonite, a plutonic-hosted copper-gold polymetallic system. D. Pyrite, sphalerite, and quartz-dolomite alteration zone in granite-porphyry at Vinasale Mountain, a peraluminous granite-porphyry-hosted gold polymetallic deposit. E. Massive stibnite vein from a Ganes-Yankee Creek dike swarm, a peraluminous granite-porphyry-hosted gold polymetallic deposit. F. Tourmaline-quartz syenite breccia from breccia pipe at Tolstoi, a plutonic-related, boron-enriched silver-tin polymetallic deposit. G. K feldspar alteration rimming tourmaline vein at the Tolstoi deposit. H. Chalcopyrite-pyrite-galena mineralization, at Cirque, a plutonic-related, boron-enriched silver-tin polymetallic deposit. I. Tourmaline-cassiterite-sulfosalt breccia pipe in Granite Mountain intrusion, a plutonic-related, boron-enriched silver-tin polymetallic deposit. J. En echelon tourmaline (dravite) near silver-bearing veins in the Tatalina pluton, considered a prospective plutonic-related silver-tin polymetallic mineral zone. K. Cassiterite-ferricrete-axinite-quartz veins and breccia in hornfels at Bismarck Creek, a plutonic-related, boron-enriched silver-tin polymetallic deposit. L. Auriferous stibnite-cinnabar-quartz mineralization at the Kolmakof mine, a precious metal-bearing epithermal system. M. Auriferous chalcedonic veins in flysch at the Poison Creek caldera complex. N. Plant imprint in chalcedonic breccia from the Bogus Creek epithermal system; sample contained 1,190 ppb Au, 940 ppm Ag, 118 ppm Sb, and 11.7 ppm Hg. O. Cinnabar-bearing placer gold nugget (884 fineness) from Snow Gulch, Donlin district. P. Very coarse quartz gold (927 fineness) nugget from Ganes Creek drainage; gold-bearing hard-rock deposits are found about 150 m upstream from nugget concentration.

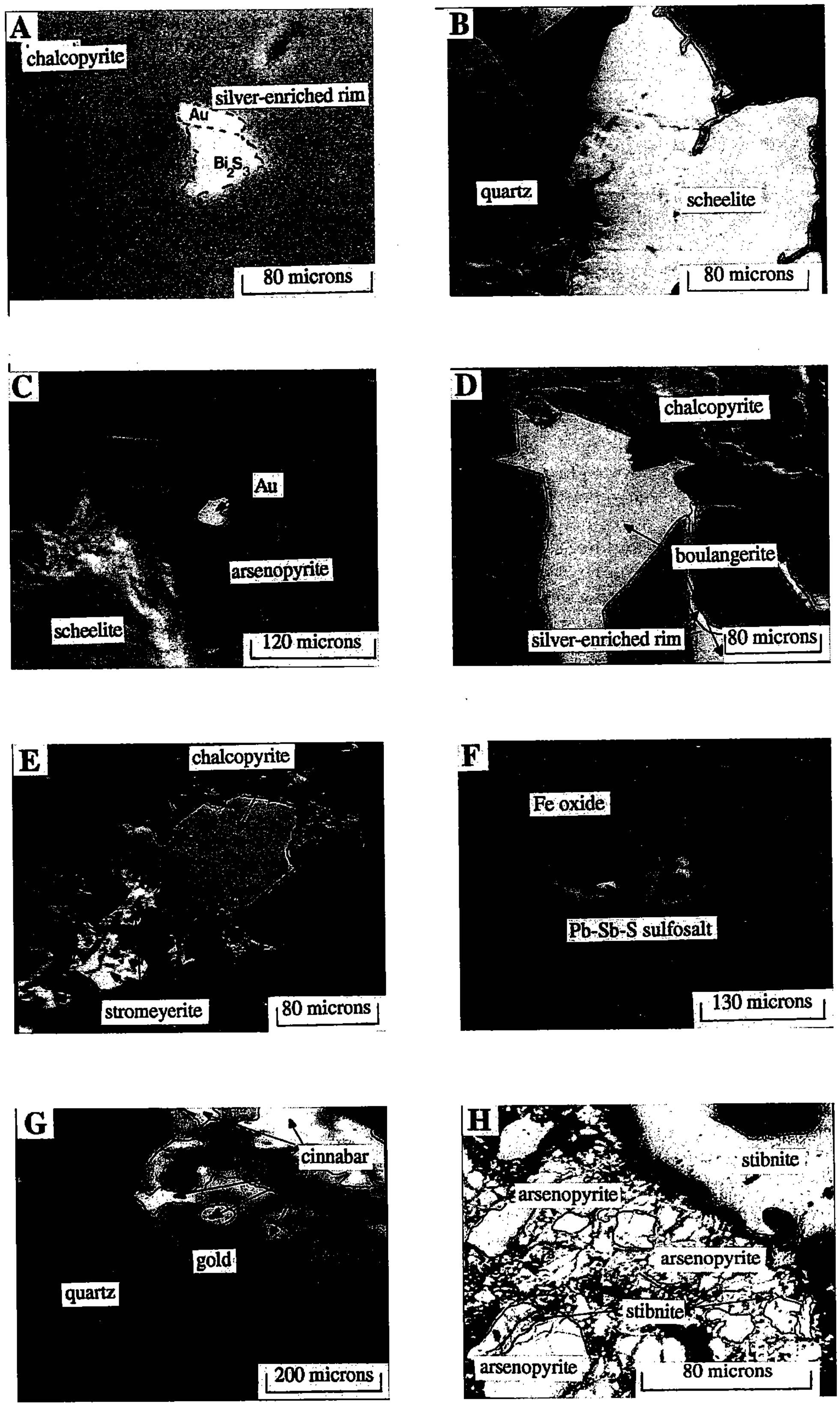


FIG. 8. Photomicrographs from selected mineral deposits in the Kuskokwim mineral belt, illustrating paragenetic relationships between sulfide and sulfosalt minerals. Photomicrographs by Cannon Electron Microprobe, Inc. A. Gold with bismuthinite in chalcopyrite from the Owhat prospect, a plutonic-hosted copper-gold polymetallic deposit. B. Scheelite containing 0.6 percent molybdenum in lattice substitution, from the Golden Horn plutonic-hosted copper-gold polymetallic

TABLE 5. Schematic Summary Illustrating Mineralogical and Temperature Zonation of Mesothermal, Precious, and Base Metal Stockwork and Vein Deposits, and of Epithermal Gold-Mercury-Antimony Veins on Chicken Mountain and in the Golden Horn Area, Flat District

Mineral deposits[1]	Alteration	Mineral assemblage	Geothermometry estimates	Generalized temperature-pressure conditions
Chicken Mountain (event 4)	Dickite, weakly silicic	Cinnabar + stibnite + gold + quartz	NA	Epithermal
Flat airstrip		Cinnabar + quartz + stibnite	NA	
Golden Horn (event 5)		Auriferous cinnabar + stibnite + quartz	NA	
Glenn Gulch (event 2)	Weakly argillic	Stibnite + boulangerite + silver sulfosalts	NA	Lowest mesothermal or epithermal
Golden Horn (event 4)		Boulangerite + arsenopyrite + owyheeite + stromeyerite	148°C based on average homogenization temperature (n = 8) of fluid inclusions in quartz	
Chicken Mountain (event 3)		Pyrite + arsenate + silver sulfosalts	NA	
Golden Horn (event 3)	Chloritic and dolomitic	Arsenopyrite + scheelite + tetrahedrite + gold + quartz; trace chalcopyrite	NA	Lower mesothermal
Minnie Gulch		Barite + boulangerite + gold	NA	
Chicken Mountain (event 2)		Chalcopyrite + molybdenite + chalcopyrite + arsenopyrite + quartz	239°C based on average homogenization temperature (n = 14) of fluid inclusions in quartz	
Golden Horn (event 2)	Strong ankerite alteration; local fluorite introduction	Chalcopyrite + galena + arsenopyrite	330°C based on arsenopyrite geothermometer	Mesothermal
Glenn Gulch (event 1)		Arsenopyrite	NA	
Golden Horn (event 1)	Deuteric-magmatic	Muscovite + biotite + ilmenorutile + quartz	401°C based on decrepitation temperature prior to homogenization	Upper mesothermal or hypothermal
Deepest zone, Chicken Mountain (event 1)		Muscovite + biotite + ilmenorutile + cassiterite(?) + quartz	387°C based on decrepitation temperature prior to homogenization	

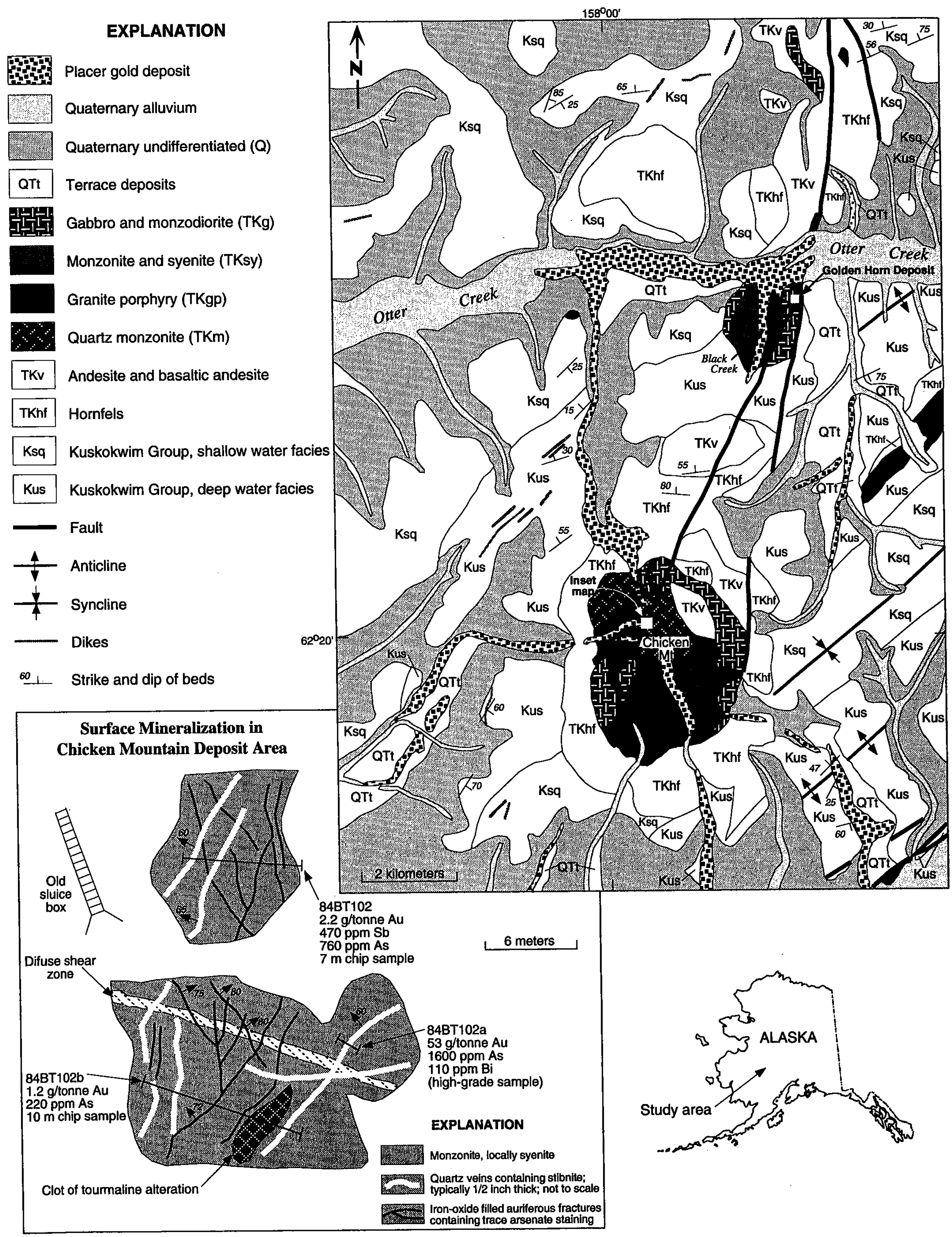
All data from Bundtzen et al. (1992) and this study; NA = not available

[1] Mineral events refer to the paragenetic position of a mineral assemblage for each deposit, based on age and crosscutting relationships

and Laird, 1983b). An ankerite alteration zone ranging from 5 to 15 m wide can be traced for about 350 m along the faulted(?) contact between augite-rich, olivine monzonite and basaltic andesite. Thin quartz veinlets containing anomalous gold, antimony (stibnite), and arsenic cut the alteration halo. This mineralized zone occurs within a larger (500 by 40 m), elliptically shaped zone of anomalous gold (200 ppb) in soils (P. Rush, written commun., 1990). Chalcopyrite-quartz-epidote veins are conspicuously abundant in overlying, propylitically altered, basaltic andesite of the Candle Hills volcanic-plutonic complex. Abundant mercury (cinnabar) and anomalous platinum metals were identified in dredge concentrates at Candle Creek, but the lode sources for these metals remain unknown. The Candle Hills pluton yielded a K-Ar biotite age of 69.7 Ma (Bundtzen and Laird, 1983b).

The Owhat, Headwall, and Mission Creek deposits in the Russian Mountains 30 km northeast of Aniak are fracture controlled, gold polymetallic-tourmaline-axinite veins that are structurally controlled along joints oriented N 25° W in quartz syenite of the Russian Mountains pluton (Figs. 1, 2). Each deposit contains major arsenopyrite and chalcopyrite and minor amounts of antimony sulfosalts, cobalt-rich pyrite, cassiterite, metazeunerite ($Cu(UO_2)_2 \cdot (AsO_4)_2 \cdot 8H_2O$), and galena. Unlike most other plutonic-hosted copper-gold polymetallic deposits in the Kuskokwim mineral belt, the Russian Mountains deposits contain large amounts of tourmaline and axinite alteration in both sheeted veins and disseminated in quartz syenite host rock. Lens-shaped ankerite alteration halos up to 50 m wide envelop all three deposits. Combined with other occurrences, the three deposits form a northwest-trending zone of mineralization 4 km long by 2 km wide in the eastern portion of the Russian Mountains pluton. In addition to gold,

deposit. C. Gold in arsenopyrite, also from the Golden Horn deposit. D. Boulangerite (with silver-enriched rims) in chalcopyrite, from the Cirque plutonic-related, boron-enriched silver-tin polymetallic deposit. E. Stromeyerite in association with chalcopyrite, from the Tolstoi plutonic-related, boron-enriched silver-tin polymetallic deposit. F. A Pb-Sb-B sulfosalt in iron oxide, from the Bismarck Creek plutonic-related, boron-enriched silver-tin polymetallic deposit. G. Cinnabar in association with gold in concentrate, from the Kolmokof area. H. Late stibnite as a cementing agent in arsenopyrite, from the Glenn Gulch precious metal-bearing epithermal vein.


EXPLANATION
Placer gold deposit
Quaternary alluvium
Quaternary undifferentiated (Q)
QTt Terrace deposits
Gabbro and monzodiorite (TKg)
Monzonite and syenite (TKsy)
Granite porphyry (TKgp)
Quartz monzonite (TKm)
TKv Andesite and basaltic andesite
TKhf Hornfels
Ksq Kuskokwim Group, shallow water facies
Kus Kuskokwim Group, deep water facies
Fault
Anticline
Syncline
Dikes
Strike and dip of beds
158°00'
62°20'
N
Otter Creek
Golden Horn Deposit
Black Creek
Inset map
Chicken Mt
2 kilometers
Surface Mineralization in Chicken Mountain Deposit Area
Old sluice box
84BT102
2.2 g/tonne Au
470 ppm Sb
760 ppm As
7 m chip sample
6 meters
Difuse shear zone
84BT102a
53 g/tonne Au
1600 ppm As
110 ppm Bi
(high-grade sample)
84BT102b
1.2 g/tonne Au
220 ppm As
10 m chip sample
Clot of tourmaline alteration
EXPLANATION
Monzonite, locally syenite
Quartz veins containing stibnite; typically 1/2 inch thick; not to scale
Iron-oxide filled auriferous fractures containing trace arsenate staining
ALASKA
Study area

copper, and arsenic, the Russian Mountains deposits contain anomalous tin, uranium, silver, cobalt, and bismuth. Electron microprobe analysis indicated that gold accompanied bismuth in association with both arsenopyrite and chalcopyrite (Fig. 8A). Limited electron microprobe analyses reported by Bundtzen and Laird (1991) show 29.0 to 33.0 at wt percent arsenic in arsenopyrite. Using techniques described by Kretschmar and Scott (1976), arsenic crystallization temperatures would be approximately 320°C for arsenopyrite in the Owhat deposit. Bundtzen and Laird (1991) estimated that 229,000 t grading 4.5 g/t gold, 2.0 percent copper, and 5 to 9 percent arsenic exists in the three deposits. The quartz syenite pluton, which intrudes a shoreline facies of the Kuskokwim Group basin-fill sequence, yielded a K-Ar biotite age of 70.3 Ma.

The Wattamuse and Ikuk prospects in the Goodnews Bay quadrangle contain quartz-carbonate-sulfide-gold veins, stockworks, and disseminations that are hosted in two small composite plutons of dioritic to quartz monzonitic composition (Figs. 2, 10). Volcanic rock remnants of an eroded volcanic-plutonic complex crop out southeast of the Wattamuse Creek prospect. The Late Cretaceous-early Tertiary igneous complexes of Wattamuse and Ikuk intrude Paleozoic-Mesozoic rocks of the Goodnews terrane. Both prospects contain chalcopyrite, arsenopyrite, and stibnite and have yielded assays of up to 9.5 g/t gold. Arsenic averaged 0.08 percent over an area 300 by 300 m at Ikuk; realgar is associated with mineralized zones at Wattamuse. Linear zones of silicic, propylitic, and sericitic alteration measuring 20 to 30 m wide parallel the quartz-carbonate-sulfide-gold veins at both prospects (Hickok, 1990a, b).

Copper-gold-bismuth skarn deposits occur in Ordovician limestone of the Telsitna Formation, which forms part of the Nixon Fork terrane about 50 km northeast of McGrath (Figs. 1, 2). Prior to 1960, about 1,850 kg (57,500 oz) of gold were recovered from ores averaging about 50 g/t gold, which contained credits of copper and bismuth. According to Herreid (1966), the deposits consist of chalcopyrite, pyrite, bornite, and native bismuth in irregular replacement bodies in skarn within 150 m of the 68 Ma Nixon Fork pluton (Moll et al., 1981). Gangue minerals include abundant garnet, diopside, epidote, and apatite. Newberry et al. (1997) provide detailed descriptions concerning classification and genesis of the skarn deposits at Nixon Fork. Consolidated Nevada Goldfields Corporation is currently developing the property into a small, high-grade underground lode gold mine. The most recent calculations available put mineable reserves at 85,348 t grading 48.4 g/t gold, with credits of silver, copper, and bismuth. Active mine production began in October 1995.

Most of the plutonic-hosted copper-gold polymetallic deposits in the Kuskokwim mineral belt are associated with mineralized plutons that intrude Cretaceous flysch. The mineralized pluton at Nixon Fork is probably a plutonic-hosted copper-gold polymetallic system; however, the Nixon Fork pluton intrudes Paleozoic limestone, which has resulted in the formation of a copper-gold-bismuth skarn.

Peraluminous granite-porphyry-hosted gold polymetallic deposits

Gold resources associated with peraluminous granite-porphyry sills, dikes, and stocks have only recently been identified in the central Kuskokwim Mountains, although their association with placer gold has been known for years (Mertie, 1936; Bundtzen and Laird, 1980; Bundtzen, 1986). As of this writing, deposits of the peraluminous granite-porphyry-hosted gold polymetallic type contain an estimated 136,500 kg gold, or 84 percent of the lode gold resources in the Kuskokwim mineral belt (Table 2).

The best examples of granite-porphyry gold deposits are Donlin Creek, in the Iditarod quadrangle; the Ganes-Yankee Creek dike swarm, in the Innoko district and also in the Iditarod quadrangle; the Ophir-Little Creek dike swarm, in the southern Ophir quadrangle; and Vinasale Mountain, about 25 km south of McGrath, in the McGrath quadrangle (Fig. 2, Table 2). Other peraluminous granite-porphyry gold occurrences include the Granite Creek and Julian Creek prospects, 55 km east of Flat, in the Iditarod quadrangle (Bundtzen et al., 1986; Miller and Bundtzen, 1994); and the Arnold, Kako, and Stuyahok prospects, in the Marshall-Anvik district (Fig. 1, 2). Most of the peraluminous granite-porphyry-hosted gold polymetallic deposits are associated with structurally controlled regional dike swarms and sill complexes; however, the Vinasale deposit is hosted in a circular hypabyssal pluton.

Auriferous mineralization occurs as (1) finely disseminated gold-bearing arsenopyrite and arsenate minerals in granite-porphyry and alaskite, including gold-quartz replacements of primary igneous phenocrysts, (2) free gold in quartz veins in dike-country rock contact zones, and (3) stockwork-type sulfide-quartz veinlets in silicified country rock—usually altered sandstone of the Kuskokwim Group.

Ore minerals include arsenopyrite, pyrite, complex arsenates, arsenean pyrite, stibnite, and locally, cinnabar. Silver to gold ratios range from 0.9:1 to 10.1:1 and average 1.7:1 (Table 4). Peraluminous granite-porphyry-hosted gold polymetallic deposits contain highly anomalous amounts of arsenic, silver, and antimony but are deficient in copper, lead, and zinc. Elevated tin and mercury values occur locally in mineral zones.

Argillic, phyllic, silicic, and carbonate alteration zones are spatially associated with linear fault or shear zones rather than with granite-porphyry and alaskite dikes. Supergene enrichment is absent, even in areas of extensively weathered mineralization. The metallic content, alteration style, and presence of cinnabar-quartz vugs in outcrop suggest that the peraluminous granite-porphyry-hosted gold polymetallic deposits in the study area may have formed in high-level, lower mesothermal to epithermal conditions.

Usually dike swarms contain more than one intrusive event,

FIG. 9. Generalized geology of the Iditarod-Flat district, showing locations of gold-bearing plutons at Black Creek and Chicken Mountain. Note the radial distribution of placer gold deposits surrounding the mineralized plutons. Inset shows style of mineralization at the Chicken Mountain gold polymetallic deposit. From Bundtzen et al. (1992).

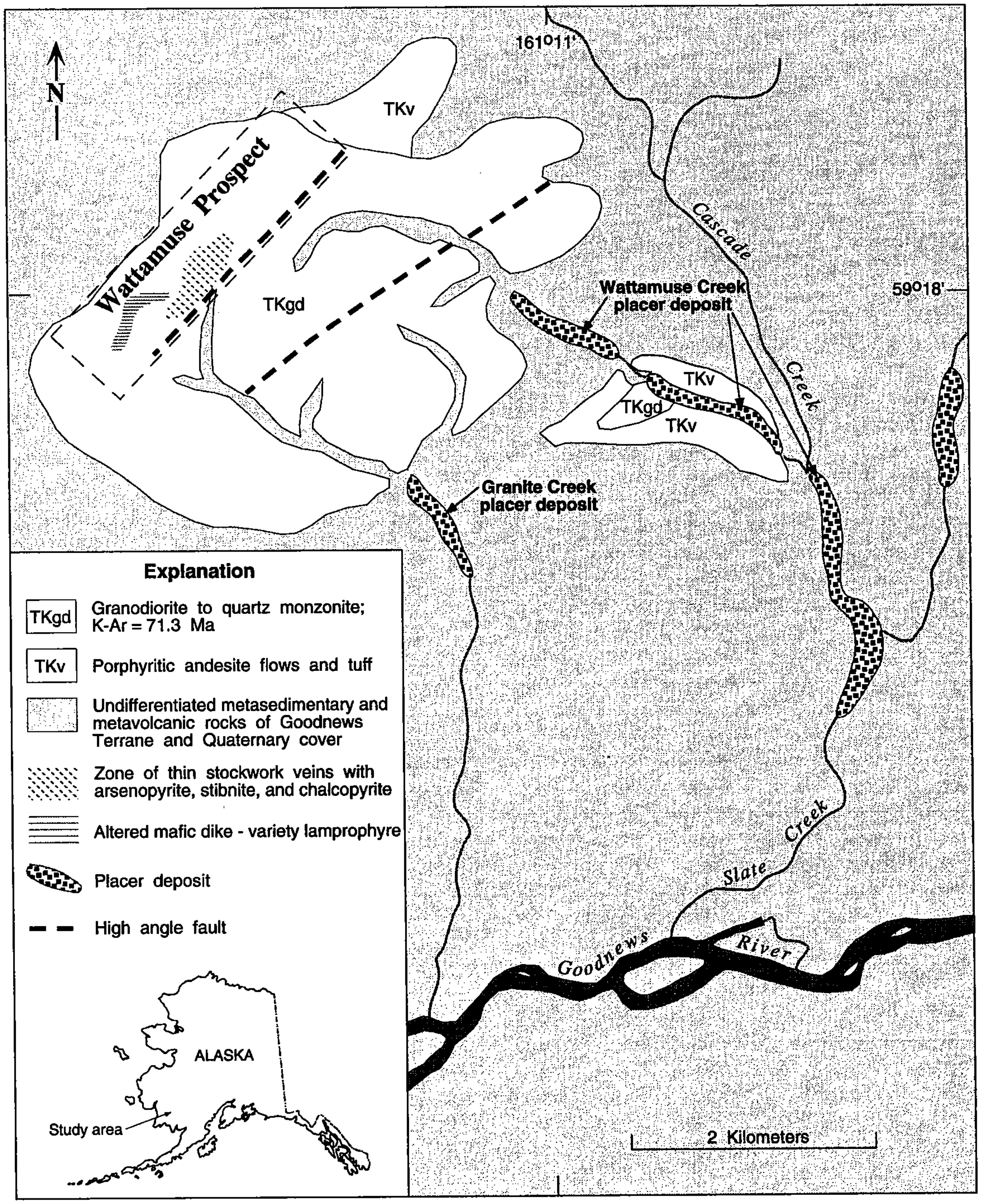


FIG. 10. Geologic sketch of the Wattamuse gold polymetallic prospect, Kuskokwim mineral belt. Geology from Hickok (1990b) and this study.

and dikes can range from granodiorite (dacite) to granite-porphyry (rhyolite) in composition (Miller and Bundtzen, 1994). K-Ar mineral ages from all eight deposits and prospects indicate pluton crystallization ages between 71 to 64 Ma (Bundtzen and Laird, 1980, 1982; Bundtzen, 1986; Miller and Bundtzen, 1994; authors, unpub. data). Mineralization ages were obtained from the Vinasale deposit and the Ophir-Little Creek dike swarm. The reported sericite age at Vinasale (68.1 Ma; DiMarchi, 1993) is approximately the same as the K-Ar biotite age of 69 Ma from the pluton (Bundtzen, 1986). Mineralized granite-porphyry from the Ophir-Little Creek dike swarm yielded a K-Ar sericite age of 71.2 Ma, which is in the same range as the crystallization ages of other nearby dikes in the Ophir area (Bundtzen and Laird, 1980).

Classification of the peraluminous granite-porphyry-hosted gold polymetallic deposits of the study area, using standard gold-bearing porphyry deposit models provided by Laznicka (1985), Cox and Singer (1986), and Hollister (1992), is problematic. Copper is absent in the peraluminous granite-porphyry-hosted deposits of the Kuskokwim mineral belt, whereas gold-bearing porphyry systems described in Cox and Singer (1986) and by Laznicka (1985) usually contain substantial copper and other elevated base metals. Concentric hydrothermal alteration zones are absent in the peraluminous granite-porphyry-hosted deposits of the study area but are usually a primary constituent of the gold-enriched porphyry model of Cox (1986b). The porphyry gold deposit model of Hollister (1992) is deficient in copper and contains abundant arsenic, like peraluminous granite-porphyry-hosted gold polymetallic deposits of the study area. However, the porphyry gold deposits of Hollister's (1992) model contain tungsten, molybdenum, bismuth, and tellurium, which are absent in peraluminous granite-porphyry-hosted gold polymetallic deposits of the study area (Table 4).

At the Donlin Creek property, which lies 25 km northeast of the Horn Mountains (Figs. 2, 11), at least three phases of mineralized felsic dikes and sills intrude Kuskokwim Group lithic sandstone and siltstone. The deposits have been briefly described by Mertie (1936) and Cady et al. (1955), and mineral resource investigations have been recently completed by the authors, private mining firms, and Calista Corporation (Retherford and McAtee, 1994). The granite-porphyry dikes and sills at Donlin Creek extend north-northeast from the Horn Mountains to the Iditarod-Nixon Fork fault just south of Chicken Mountain, a distance of about 50 km. Miller and Bundtzen (1994) reported K-Ar muscovite ages of 65.1 and 70.9 Ma from granite-porphyry sills near Snow Gulch and Dome Creek, respectively. The mineral deposits explored to date consist of seven separately defined mineralized bodies that lie along approximately 6 km of a linear dike-sill swarm emplaced along the northeast-trending Donlin fault (Fig. 11). Mineralization consists of quartz-stibnite veins in granite-porphyry and silicified sandstone, quartz gold replacements of phenocrysts, and wide vein-disseminated quartz sulfide zones that lie along shears and stockwork zones. Ore minerals include auriferous pyrite, stibnite, cinnabar, arsenopyrite, and sulfosalts. Trenching and drilling conducted from 1989 to 1990 by Westgold, Inc., indicated that seven orebodies—the Carolyn, Snow, Queen, Rochelieu, Upper Lewis, Middle Lewis, and Lower Lewis zones—contained an inferred reserve of 3,871,025 t grading 3.15 g/t gold, or 12,194 kg (392,090 oz) gold (Retherford and McAtee, 1994). Placer Dome U.S., which is conducting explorations on the property, recently announced that the Donlin Creek deposits contain 111,960 kg (3.6 million oz) gold in 40.4 Mt of mineralization (Stratman, 1996).

Gold-bearing, quartz-carbonate-sulfide veins and sulfide disseminations are hosted in peraluminous granite-porphyry of the 40-km-long Ganes-Yankee Creek dike swarm (Figs. 2, 12). The highest concentration of metallic mineralization occurs in a zone 4 by 0.5 km near the divide separating Ganes and Yankee Creeks, both drainages of which have produced at least 6,354 kg (204,330 oz) of placer gold and 863 kg (27,764 oz) of by-product silver. Most of the mineralized zones in the dike swarm consist of disseminated sulfides in dikes and quartz stockwork in sandstone adjacent to dikes. Linear zones of ankerite-sericite alteration envelop the dikes and also 5 to 15 m of the host sedimentary rocks. At the Independence deposit, disseminated arsenopyrite, pyrite, cinnabar, stibnite, stephanite, and other sulfosalts occur in dike rock and altered sandstone of the Kuskokwim Group (Fig. 8E). Free gold in quartz was identified in veins adjacent to dike-country rock contacts in several localities northeast of the Independence mine. Carbonate alteration is controlled along hairline fractures both in wall rock and at dike-sandstone contacts. The Independence deposit was briefly developed in 1912, when about 5 kg (161 oz) of gold were won from about 113 t of ore.

Farther to the southwest, the Ganes-Yankee Creek dike swarm is truncated by the Iditarod-Nixon Fork fault. Restoration of the 88 to 94 km of right-lateral offset proposed by Miller and Bundtzen (1988) for the Iditarod-Nixon Fork fault reveals that the Ganes-Yankee and Donlin Creek dike swarms formed part of the same metallogenic belt now offset by the Iditarod-Nixon Fork fault (Miller and Bundtzen, 1994; Fig. 2).

Granite-porphyry dikes and sills containing gold, antimony, and arsenic cut the Kuskokwim Group in two distinct areas in the George River basin about 60 km east of Chicken Mountain (Fig. 2). At Granite Creek three of four granite-porphyry bodies trend northeast for 25 km and are apparently the source of placer gold in Granite Creek. Gold-bearing stibnite veins occur in shear zones adjacent to the dikes (Bundtzen et al., 1986). At Julian Creek porphyry sills up to 500 m wide are also the apparent lode sources of placer gold. The two dike-sill swarms at Julian and Granite Creeks have been offset from each other right laterally by about 15 km along a northeast-trending high-angle fault (Fig. 2).

Two concentrations of granite-porphyry dike swarms and stocks and altered mafic dikes cut Kuskokwim Group clastic rocks near the abandoned mining town of Ophir, 55 km west of McGrath (Figs. 1, 2, 13). The gold-arsenic-antimony-bearing dikes are the probable source of approximately 3,380 kg (108,680 oz) of gold produced in Ophir, Spruce, Little, and Ester Creeks, which are downslope or downstream from the mineralized dike swarms. The dike swarms trend northeast for a distance of at least 25 km before disappearing in both directions under Quaternary cover. Although not clearly linked to faulting, the Ophir-Little Creek swarms trend southwest toward the high-angle Beaver Mountains fault (Bundtzen and Laird, 1982). Two gold arsenic-enriched prospects in a large granite-porphyry dike near the head of Ester Creek have been prospected with surface trenching and sampling, though with inconclusive results. Alteration in the mineralized dikes includes weakly developed argillic alteration that parallels the dike-country rock contacts. Elevated vanadium (1,500 ppm) and tungsten (100 ppm) occur in some mineralized samples. Abundant scheelite was recovered from placer operations just below the dike swarm on Little Creek. Bundtzen and Laird (1980) reported a K-Ar age of 70.1 Ma from sericite in the mineralized Ester Creek dike, which is believed to date hydrothermal alteration and mineralization.

Mineralized granite and quartz porphyry dikes and sills cut altered metabasalt of the arc-related Koyukuk terrane at the Arnold or Willow Creek prospect, about 25 km east of Marshall in the Marshall-Anvik district (Figs. 1, 2). Three N 55° W-trending dikes that can be traced for approximately 230 m of strike length have steep dips and contain most of

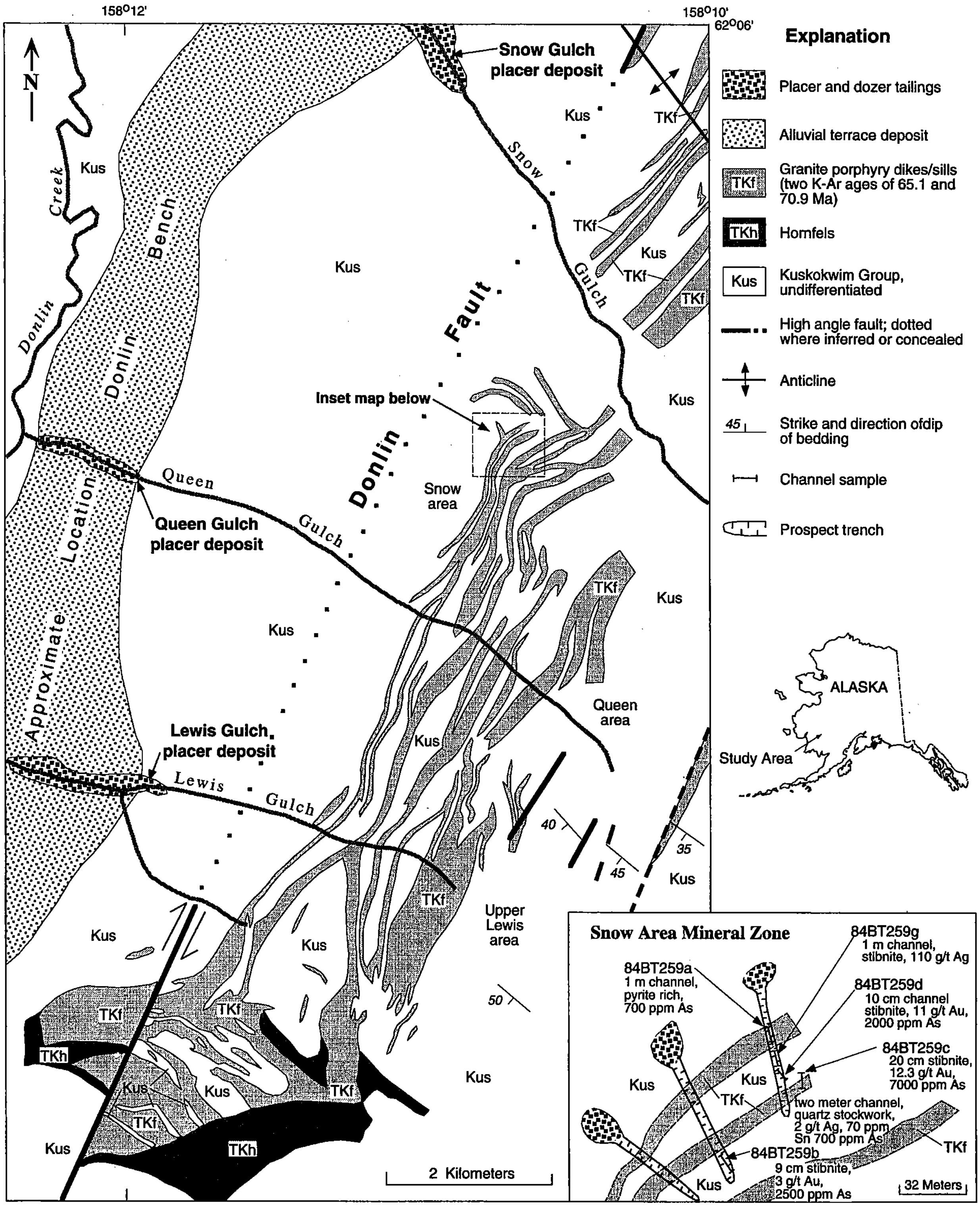


FIG. 11. Geology of the Donlin Creek dike swarm, adapted from Retherford and McAtee (1994). Inset from this study.

the known gold mineralization. The Arnold prospect was dug to explore a quartz vein stockwork with scattered small breccia zones hosted in andesite tuff. Sulfide mineralization is chiefly arsenopyrite and pyrite, but minor amounts of molybdenite and chalcopyrite also occur. Silica-iron-carbonate alteration forms a large halo of up to 40 m around the mineralized zones. Chip-channel samples collected during this study contain 3.4 to 28 g/t gold and anomalous molybdenum, arsenic, copper, lead, and silver. The Arnold and related prospects are thought to be the source of approxi-

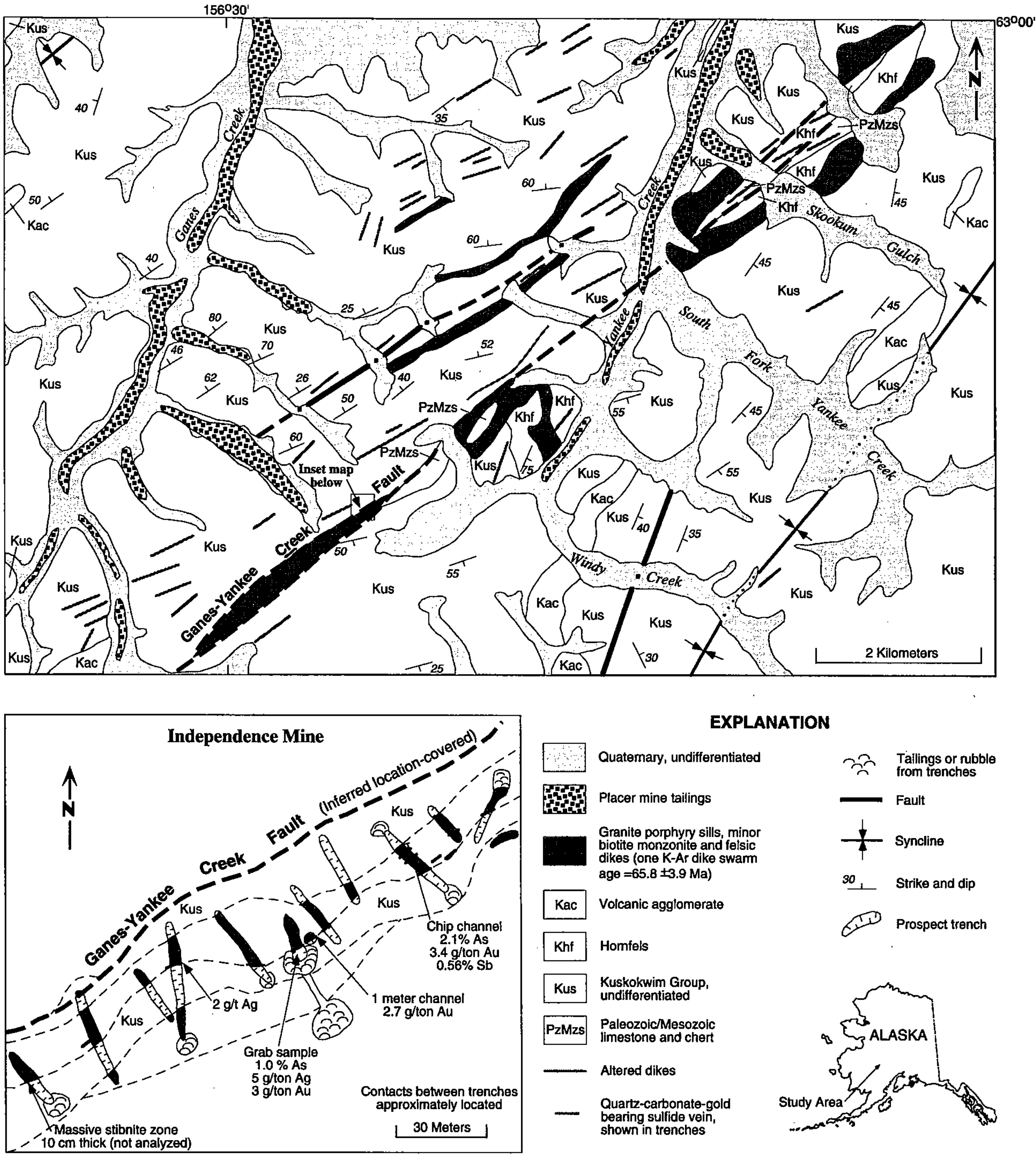


FIG. 12. Geology of part of the Ganes-Yankee Creek dike swarm, Innoko district, Kuskokwim mineral belt, showing the location of the Independence lode gold mine and distribution of heavy mineral placer deposits. Data modified from Bundtzen and Laird (1982, 1983a).

mately 3,450 kg (110,930 oz) of gold won from placer deposits mined in nearby Willow Creek. One K-Ar biotite age of 65 Ma was obtained from a mineralized intrusion near the prospect. Similar granite-porphyry dikes and sills are the presumed lode sources of placer gold in the Kako Creek and Stuyahok areas, which are located in the eastern extensions of the Marshall-Anvik gold district (Fig. 2). At Stuyahok, granite-porphyry and alaskite sills and dikes that intrude Neocomian volcaniclastic rocks of the Yukon-Koyukuk terrane are found directly underneath commercial placer gold deposits.

A mineralized, multiphased, 6-km^2 pluton consisting of monzonite, quartz monzonite, and granite-porphyry intruded the Kuskokwim Group at Vinasale Mountain, about 25 km south of McGrath. Recent industry exploration efforts summarized by DiMarchi (1993) have delineated one of the most

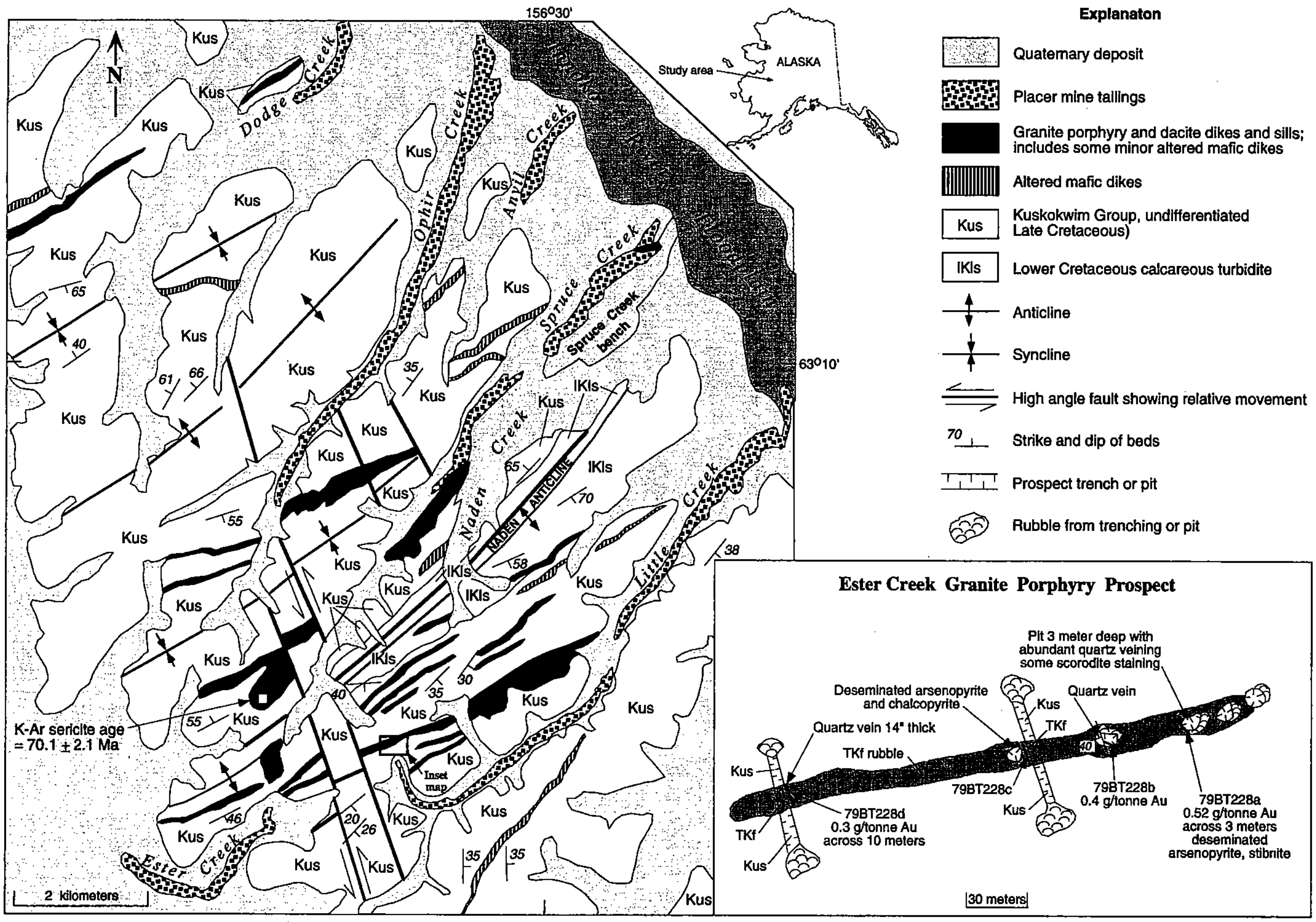


FIG. 13. Geology of the Ophir-Little Creek auriferous dike swarm, Innoko district, Kuskokwim mineral belt, illustrating the relationship between mineralized dikes and commercial placer gold deposits. Data adapted from Bundtzen and Laird (1980).

important lode gold resources in the Kuskokwim mineral belt (Fig. 14). A 1:63,360-scale reconnaissance geologic map of the area (Bundtzen, 1986) included descriptions of placer and lode deposits in Alder Creek (a southerly gulch draining Vinasale Mountain) and also reported a K-Ar biotite age of 69 Ma from a quartz monzonite phase of the intrusion. According to DiMarchi (1993), mineralization occurs as disseminations, breccias, dolomite veins, and segregations wholly hosted in intrusive phases of the Vinasale pluton. Alteration identified during mineral exploration include silicification, sericitization, dolomitization, and propylitic replacement of mafic minerals (Fig. 7D). The largest and most significant concentrations of gold in the Central zone are introduced into areas of intense sericite alteration and silica flooding; over 90 percent of the gold is contained in sulfides and sulfosalts of arsenic and antimony (DiMarchi, 1993). Based on about 11,260 m of drilling, the Central zone of the Vinasale deposit is estimated to contain about 10.3 Mt of ore grading 2.40 g/t gold and credits of silver and antimony, or about 24,540 kg (789,000 oz) of in-place gold resources. Further detailed information on the Vinasale deposit is provided by McCoy et al. (1997).

Plutonic-related, boron-enriched silver-tin polymetallic deposits

Small meta-aluminous to peraluminous, alkali-calcic to calc-alkaline, hornblende-bearing intermediate to felsic plutons and volcanic-plutonic complexes that range in age from 71 to 59 Ma are associated with boron-enriched silver-tin polymetallic deposits throughout the Kuskokwim mineral belt. The best examples in the study area include the Cirque, Tolstoi, Granite Mountain, and Bismarck Creek deposits in the Iditarod quadrangle (Fig. 2). Similar mineralization has been described at the Win and Won deposits (Burleigh, 1992a, b), northwest of McGrath, and in a tin-silver occurrence on the Cosna River (Burleigh, 1989), 300 km northeast of McGrath, a probable extension of the Kuskokwim mineral belt. Approximately 20 additional prospects and occurrences of this deposit type are described in the Iditarod quadrangle (M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun., 1996).

Host plutons of the silver-tin polymetallic deposit type can range from diorite to quartz monzonite but are generally less differentiated than the intrusions that host the copper-gold

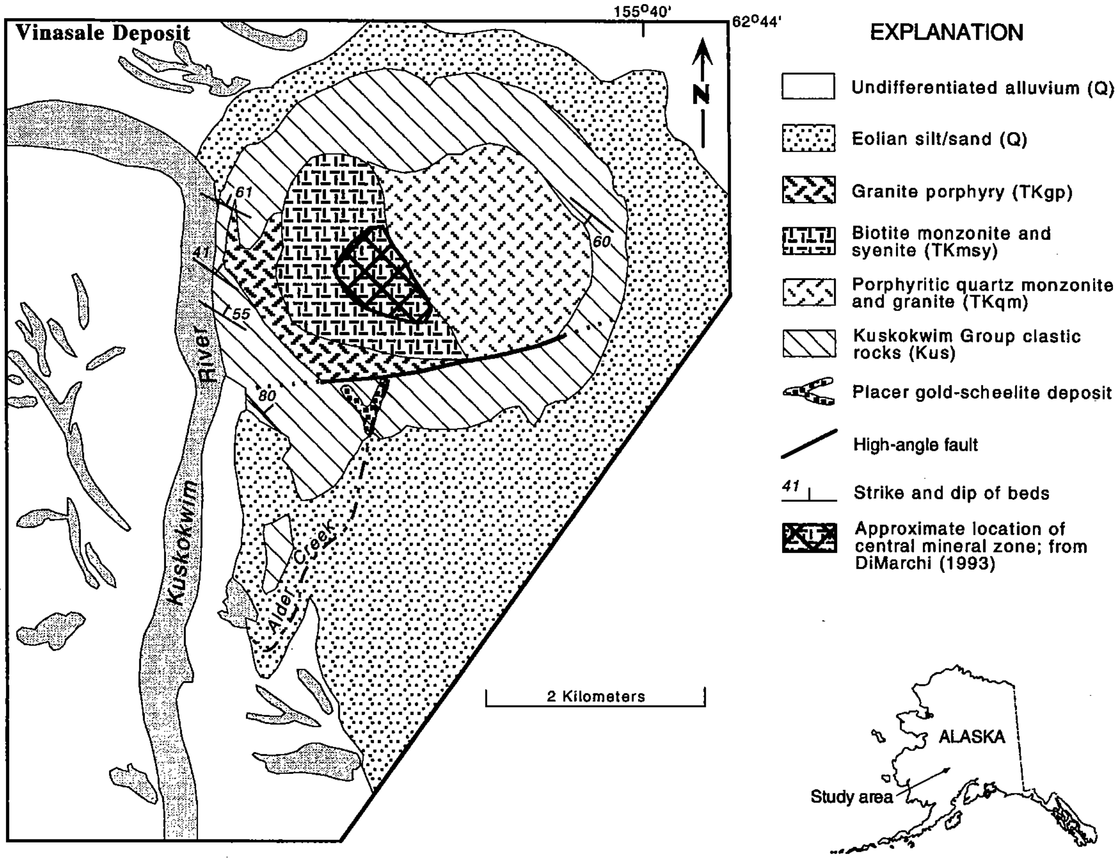


FIG. 14. Geology of the Vinasale Mountain gold deposit, southwestern Alaska, showing location of the Central zone, the main concentration of auriferous mineralization. Regional geology by Bundtzen (1986).

polymetallic deposit type. Hornblende is common in the silver-tin polymetallic plutons, whereas it is generally absent in plutons associated with copper-gold polymetallic mineralization. Although extensive boron metasomatism (introduction of large amounts of tourmaline and axinite) is characteristic of silver-tin polymetallic systems, this alteration type is sometimes also associated with the plutonic-related copper-gold polymetallic deposits described earlier.

Silver-tin polymetallic mineralization in the study area exhibits the following morphological types: (1) circular or dumbbell-shaped tourmaline-axinite breccia pipes in plutons and/or overlying hornfels (Fig. 7F, I), (2) en echelon tourmaline-quartz stockwork in cupolas of plutons (Fig. 7J), and (3) large boron-replacement zones in hornfels breccia and altered volcanic rocks, where the presence of brown to purple axinite is characteristic (Fig. 7K). Multiple phases of sulfides and oxides including cassiterite, chalcopyrite, sphalerite, arsenopyrite, bismuth sulfosalts, and ilmenorutile accompany the boron deposits. Deposits occur in both intrusive cupolas and hornfels aureoles in almost equal amounts.

Alteration consists mainly of extensive boron metasomatism in the form of ferro-axinite and tourmaline, accompanied by anatase and extensive ferricrete oxidation. Potassium feldspar alteration haloes are often found rimming tourmaline veins (Fig. 7G).

Silver to gold ratios from three representative deposits widely range from 347:1 to 6,525:1 and average 3,072:1 (Table 4). The plutonic-related, boron-enriched silver-tin polymetallic deposits contain elevated levels of arsenic, antimony, copper, lead, zinc, niobium, and bismuth. Anomalous indium (118 ppm) was found in the Tolstoi and Bismarck Creek deposits, respectively. Other prospects and occurrences of this deposit type in the study area, which have been briefly described by Szumigala (1995) and by M.L. Miller, T.K. Bundtzen, and J.E. Gray (written commun., 1996), also contain high silver to gold ratios and elevated tin, zinc, lead, and bismuth values. The anomalous tin, zinc, silver, and bismuth contents, the high silver to gold ratios, and the alteration style seem to distinguish this type of deposit from other plutonic-related deposit types in the Kuskokwim mineral belt described in this paper.

Three plutons that host plutonic-related, boron-enriched silver-tin polymetallic deposits yielded K-Ar biotite crystallization ages of 63 to 59 Ma, distinctly younger than those of other mineralized plutons in the study area. However, the Beaver Mountains and Moore Creek plutons, which contain mineralization of this type, yield K-Ar mineral ages averaging 70 Ma, or the same as other mineralized plutons.

Bundtzen and Gilbert (1983) noted that tin-bearing polymetallic deposits in the Beaver Mountains and on Tatalina Mountain were similar to porphyry-related boron-silver-tin systems described by Sillitoe et al. (1975), and probably not

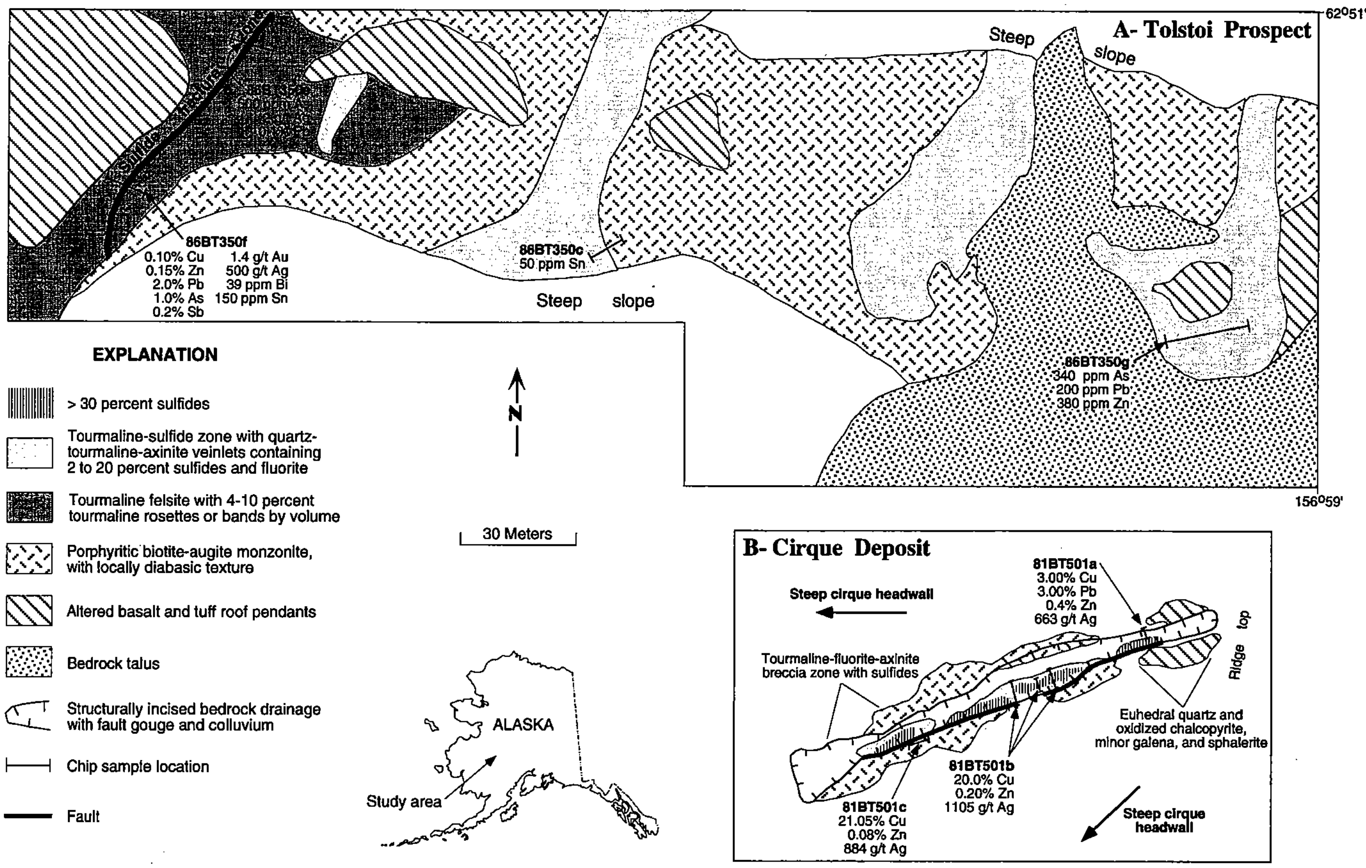


FIG. 15. Two examples of high-level, plutonic-related, boron-enriched silver-tin polymetallic mineralization in the Beaver Mountains. A. Tolstoi prospect, illustrating extensive tourmaline-sulfide breccia zones (geologic traverse along a steep ridge line). B. Cirque copper-silver (gold) deposit, showing N 70°E fracture zone and tourmaline-axinite-fluorite breccia zone. Both deposits occur just below roof pendants of basaltic andesite.

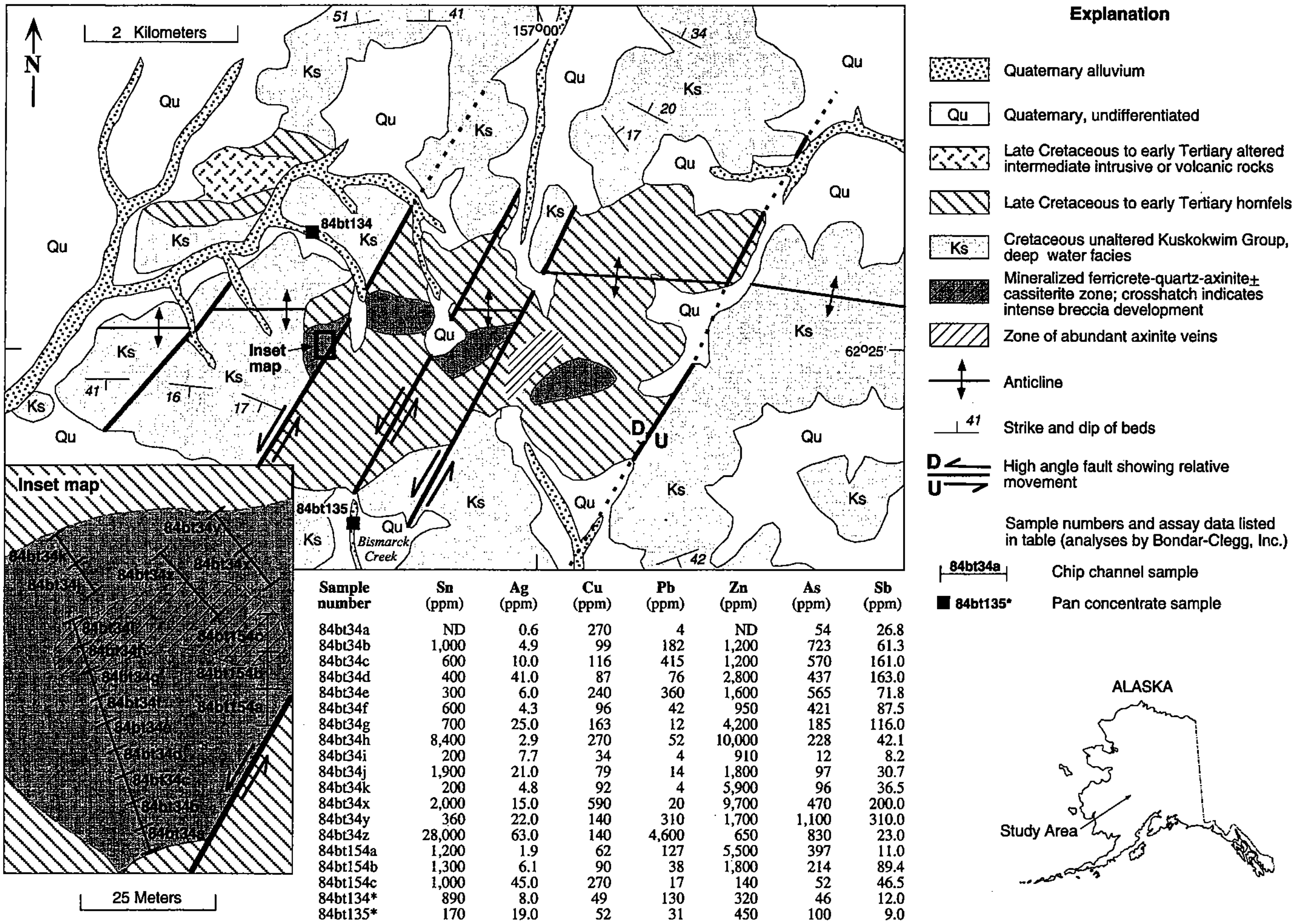
similar to tin greisen, porphyry, or vein deposits typified by those in Cornwall, England (Hosking, 1970) or Lost River (Sainsbury, 1969; Hudson and Arth, 1983) and Sleitat, Alaska (Burleigh, 1991). The latter two deposits are usually associated with muscovite and/or biotite leucogranite (S type) and accompanied by wolframite, topaz, and REE minerals. The plutonic-related silver-tin polymetallic deposits of the Kuskokwim mineral belt most likely correspond to both 20a (porphyry Sn; Reed, 1986) and 20b (Sn polymetallic; Togashi, 1986) deposit models.

Late Cretaceous-early Tertiary volcanic and plutonic rocks in the Beaver Mountains (Fig. 2) host a variety of mineralized veins, breccia pipes, and replacement bodies that contain anomalous Ag, Cu, Pb, W, Sn, Nb, and As; the largest zones of mineralization found to date occur in the Tolstoi and Cirque deposits (Figs. 2, 15, Table 4). The Cirque deposit consists of parallel tourmaline-axinite-sulfide fracture fillings in a high-level cupola of quartz syenite belonging to the Beaver Mountains pluton (Bundtzen and Laird, 1982). The mineralization extends vertically for at least 250 m but is capped by a volcanic roof pendant. Copper and silver values (up to 21% and 1,108 g/t, respectively) were obtained from channel samples at the Cirque deposit (Fig. 7H). Sixteen samples from several levels of the Cirque deposit averaged 0.078 percent tin (Table 4).

The nearby Tolstoi deposit consists of several parallel tourmaline-sulfide breccia zones in a cupola position of the Beaver Mountains stock (Fig. 7F, G). The mineralization, which consists of arsenopyrite, chalcopyrite, and pyrite, is similar to that observed at the Cirque deposit, except that sulfides at the Tolstoi deposit are more disseminated in nature and boron replacement is more extensive (Fig. 15). Silver-rich sulfosalts including stromeyerite and boulangerite were found in association with chalcopyrite in the Tolstoi and Cirque deposits; the presence of these minerals may explain the relatively high silver content observed in the high-grade copper mineralization at both localities (Fig. 8D, E, Table 4).

Boron-enriched silver-copper-quartz veins cut a small monzonite pluton at the Broken Shovel prospect, about 70 km southwest of McGrath (Figs. 1, 2). The 4-km^2 pluton, which yielded a K-Ar biotite age of 68.3 Ma, intrudes the Upper Cretaceous Kuskokwim Group flysch. The chalcopyrite-arsenopyrite-quartz vein trends for 200 m in a northeast direction and features en echelon sheeted tourmaline veins nearly 30 m thick that extend along the hanging wall for the entire length of the deposit. Silver to gold ratios average 555:1; six analyses average 0.25 percent arsenic, 0.24 percent antimony, 0.07 percent lead, and 0.48 percent copper (Bundtzen et al., 1988).

Silver-bearing, boron-enriched quartz-sulfide-tourmaline-



Sample number	Sn (ppm)	Ag (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	As (ppm)	Sb (ppm)
84bt34a	ND	0.6	270	4	ND	54	26.8
84bt34b	1,000	4.9	99	182	1,200	723	61.3
84bt34c	600	10.0	116	415	1,200	570	161.0
84bt34d	400	41.0	87	76	2,800	437	163.0
84bt34e	300	6.0	240	360	1,600	565	71.8
84bt34f	600	4.3	96	42	950	421	87.5
84bt34g	700	25.0	163	12	4,200	185	116.0
84bt34h	8,400	2.9	270	52	10,000	228	42.1
84bt34i	200	7.7	34	4	910	12	8.2
84bt34j	1,900	21.0	79	14	1,800	97	30.7
84bt34k	200	4.8	92	4	5,900	96	36.5
84bt34x	2,000	15.0	590	20	9,700	470	200.0
84bt34y	360	22.0	140	310	1,700	1,100	310.0
84bt34z	28,000	63.0	140	4,600	650	830	23.0
84bt154a	1,200	1.9	62	127	5,500	397	11.0
84bt154b	1,300	6.1	90	38	1,800	214	89.4
84bt154c	1,000	45.0	270	17	140	52	46.5
84bt134*	890	8.0	49	130	320	46	12.0
84bt135*	170	19.0	52	31	450	100	9.0

FIG. 16. Generalized geologic map of plutonic-related, boron-enriched silver-tin polymetallic mineralization at Bismarck Creek, central Iditarod quadrangle. Inset shows the mineralization in the westernmost hornfels breccia zone. Data from this study.

manganese-axinite stockwork covers an elliptically shaped zone 200 m^2 in hornfels sandstone above syenite intrusive rocks of the Tatalina Mountain pluton about 35 km west-southwest of McGrath (Figs. 2, 7J). Several prospect pits expose the better mineralization and yielded values up to 5 g/t silver, 100 ppm copper, and locally up to 0.5 percent lead. Pan concentrates from nearby Carl Creek, which has headwaters in the northern portion of the mineralized zone, have yielded up to 2,000 ppm bismuth, 23 g/t silver, and 500 ppm tin. Based on geochemistry, mineralogy, and alteration, this poorly explored mineralized zone is classified as a plutonic-related, boron-enriched silver-tin polymetallic system. Bundtzen and Laird (1983a) reported a K-Ar biotite age of 61 Ma from the underlying syenite intrusion.

An east- to northeast-trending zone of quartz-cassiterite-tourmaline-axinite gossan in a large sandstone hornfels aureole 12 km^2 was discovered on a ridge line at the head of Bismarck Creek, a tributary to the George River (Figs. 2, 16). No pluton is exposed, but a hornblende-bearing volcanic(?) unit crops out about 5 km west-northwest of the hornfels aureole (Miller and Bundtzen, 1994). Secondary biotite is locally abundant in the hornfels aureole and occurs as dark red, fine-grained network veins, clots, and replacement zones in breccia. A 30-m-wide mineralized zone in the westernmost part of the hornfels aureole can be traced for about 300 m along strike, before disappearing underneath vegetative cover. Three other similar ferricrete-quartz-axinite-cassiterite breccia zones occur in the prominent hornfels aureole. Black cassiterite has been identified in late-stage veins, but only traces of a lead-antimony sulfosalt, galena, and sphalerite were found, probably owing to extensive surface oxidation (Figs. 7K, 8F). Silver values from chip-channel samples range from 2 to 63 g/t; tin values from the same samples range from trace amounts to 2.80 percent. Based on extensive surface sampling and geologic modeling, the Bismarck Creek deposit has an inferred reserve of 498,000 t grading 0.137 percent tin, 47.8 g/t silver, 0.16 percent copper, and 0.26 zinc and contains anomalous fluorine, bismuth, antimony, indium, and lead.

Silver-tin polymetallic mineralization on Granite Mountain, which is about 20 km southeast of Bismarck Creek, consists of several tourmaline breccia and tourmaline-sheeted zones in both quartz monzonite intrusive phases and surrounding volcanic and sedimentary hornfels (Miller and

Bundtzen, 1994). One tourmaline breccia zone is 400 m long, 15 m wide, and cylindrical in cross section and contains anomalous silver, tin, bismuth, and zinc (Table 4, Fig. 7I). One K-Ar biotite age of 62.6 Ma was obtained from quartz monzonite adjacent to the metasomatized host rocks.

According to Burleigh (1992a, b), mineralization at the Win and Won prospects consists of polymetallic-sulfide and quartz-cassiterite assemblages in veins and breccias within a quartz-tourmaline-altered hornfels aureole. Nearby intermediate dikes and small intrusions cut hornfels near the silver-tin polymetallic mineralization. Most of the mineralized areas at both the Win and Won deposits are extensively oxidized, and cassiterite is the main ore mineral identified. Electron microprobe analysis revealed the presence of three subtypes of lead-bismuth-antimony-silver sulfosalts. Burleigh (1992a) reported that veins and breccia veins from the Win deposit contain as much as 643 g/t silver and 6.97 percent tin; 20 high-graded samples averaged 5.16 percent tin and 388 g/t silver (Table 4). A few scattered gold anomalies were reported by Burleigh (1992a) at the Win prospect, but the average of 103 samples was below 100 ppb. Based on surface sampling, Burleigh (1992b) estimated that the Won deposit contains 1.94 Mt of mineralization grading 0.59 percent tin and 42 g/t silver. Both the Win and Won deposits also contain anomalous niobium, antimony, bismuth, indium, and selenium.

Boron-enriched silver-tin polymetallic mineralization cuts monzonite at the Pupinski prospect, about 5 km southeast of the Nixon Fork copper-gold-bismuth skarns described previously. Disseminated to locally massive pods of chalcopyrite, disseminated acanthite(?), and minor cassiterite occur in a 100-m-long, 25-m-wide, elliptical tourmaline-quartz greisenlike zone about 1 km from the southeastern margin of the Nixon Fork pluton. Limited analyses indicate the presence of up to 261 g/t silver, 4.58 percent copper, 0.11 percent zinc, 36 ppm tin, and 535 ppm tungsten (Table 4). Gold was usually below the detection limit (50 ppb) in samples analyzed for this study, and auriferous zones have not been recognized at the Pupinski prospect (R. Flanders, oral commun., 1995).

Gold-silver deposits associated with epithermal systems

Epithermal gold and silver mineralization is associated with Late Cretaceous-early Tertiary igneous rocks throughout the Kuskokwim mineral belt. We tentatively subdivide these epithermal systems into three subtypes: (1) structurally controlled (gold)-mercury-antimony deposits related to altered olivine basalt dikes, (2) low-temperature gold-antimony-mercury-bearing shear zones in high-level portions of mineralized intrusive rocks, and (3) chalcedonic breccias hosted in subaerial volcanic piles, including stockwork veins adjacent to calc-alkaline, andesite to rhyolite volcanic calderas.

Silica-carbonate, potassic-phyllic, and adularia-chalcedonic alteration predominate in the three deposit subtypes above. All epithermal gold-silver occurrences contain variable amounts of cinnabar and stibnite and are usually accompanied by silver sulfosalts and free gold. Silver to gold ratios are highly variable, ranging from 0.06:1 to 185:1 and averaging 61:1 (Table 4).

Although isotopic age dates are lacking for epithermal gold-silver deposits in the study area, several are available from the spatially related, epithermal mercury-antimony deposits. Miller and Bundtzen (1994) reported a K-Ar whole-rock age of 76 Ma from hydrothermally altered mafic basalt at the DeCourcy Mountain mercury-antimony mine (Fig. 2). Gray et al. (1992) reported a Ar^{40}/Ar^{39} plateau age of 72.5 Ma from hydrothermal sericite at the Fairview mercury-antimony deposit near Sleetmute and a Ar^{40}/Ar^{39} minimum age of 72 Ma from hydrothermal sericite at the Rhyolite mercury prospect on Juninggulra Mountain, north of the Horn Mountains (Figs. 1, 2). The Rhyolite prospect is hosted in a southwestern extension of the granite-porphyry dike and sill swarm that hosts the Donlin granite-porphyry gold polymetallic deposits described in this paper (Figs. 2, 11).

Although highly variable and poorly studied, the three gold-silver deposit subtypes associated with epithermal systems in the study area may correspond to the deposit models 25a (hot spring Au-Ag; Berger, 1986), 25b (Creede epithermal veins; Mosier et al., 1986b), and 25d (Sado epithermal veins; Mosier et al., 1986a), respectively. Gold reserves in epithermal gold-silver deposits in the study area are sparse, owing to lack of detailed exploration. A modest reserve estimate of 92 kg (2,960 oz) gold is inferred in the Dishna River deposit (Table 2).

Epithermal cinnabar-stibnite deposits of the study area are part of a well-studied mercury belt (Sainsbury and MacKevett, 1965) that extends nearly 500 km from the Red Top mine, near Bristol Bay, to Mount Joaquin, near McGrath (Fig. 1). Mercury and minor antimony has been recovered from about a dozen deposits, and 85 percent of the total 1.38 million kg (39,960 flasks) of mercury was produced from the Red Devil deposit near Sleetmute in the Aniak-Tuluksak district (Fig. 1, Table 1). These cinnabar-stibnite deposits are spatially, and probably genetically, related to the gold-silver mineralization in epithermal systems of the study area.

At the Red Devil mine, high-angle structures cut Cretaceous Kuskokwim Group flysch and altered mafic dikes. The cinnabar-stibnite-bearing fluids probably utilized the faulted mafic dikes as structural conduits, because there is no clear link to the mercury-antimony mineralization and the dikes themselves. Herreid (1962) first described vertical mineral zonation at Red Devil. Near-surface ore shoots are generally composed of quartz-cinnabar, but stibnite/cinnabar ratios increase with depth. On the fifth and deepest level, about 180 m below the surface, ore shoots consist mainly of stibnite-quartz and contain only traces of cinnabar.

Fluid inclusion studies by Roedder (1963, 1972) and H.E. Belkin (reported in Miller et al., 1989) support the contention that ore deposition took place at relatively shallow depths in the hydrothermal system. Homogenization temperatures of Red Devil cinnabar crystals range from 158° to 164°C, and in quartz gangue vein material, from 169° to 210°C (Miller et al., 1989). Assuming CO_2 densities of 0.25 g/cm^3 and trapping temperatures of 160° to 200°C, Miller et al. (1989) estimated a trapping temperature at Red Devil of 150 to 200 bars or up to 1,500 bars if inclusions were trapped in a water column. Cumulative evidence suggests that the quartz-Hg-Sb solutions at Red Devil and probably other similar deposits formed in epithermal conditions—perhaps in a hot springs environment. One unusual feature of the Red Devil deposits is the high level of hydrocarbons in fluid inclusions in both quartz and cinnabar (Roedder, 1963). Microthermometer and mass spectrometry analyses from several other Hg-Sb deposits in the study area indicate that fluid inclusions are composed of more than 95 percent H_2O and up to 4 percent CO_2 and contain trace amounts of N_2 and CH_4 (Gray et al., 1992). Gray et al. (1997) present more detailed features of the mercury-antimony lodes of southwest Alaska.

Several epithermal mercury-antimony systems in the Kuskokwim mineral belt contain anomalous gold values. Mineralization at the Kolmakof mine, 30 km east of Aniak, consists of narrow stringers of cinnabar as well as arsenopyrite in silica-carbonate-altered breccia zones and fractures within altered mafic dikes that intrude Kuskokwim Group clastic rocks (Figs. 2, 7L, 17). Chalcedonic-adularia zones have been introduced into the quartz breccias hosting the main cinnabar-stibnite zones. Bundtzen et al. (1993) reported that three samples near the largest mineralized mafic dikes contained 3.24 to 10.0 g/t gold (Figs. 8G, 17) and 0.8 to 45 g/t silver, as well as elevated values of copper (91 ppm) and cerium (1,470 ppm). Quartz-carbonate veins in bleached sandstone 75 m east of the main Kolmakof Hg-Au-Ag deposit contain 27 to 66 ppm tellurium and 24 to 54 ppm molybdenum.

Although primarily the site of plutonic-hosted copper gold polymetallic deposits, high-level mercury-antimony deposits also occur on Chicken Mountain and at the Glenn and Minnie Gulch deposits immediately north of Flat (Figs. 2, 7). Bundtzen et al. (1992) found native gold and electrum in cinnabar at the Glenn Gulch stibnite-gold-silver deposit near the Golden Horn mine (Fig. 8H) and described auriferous stibnite-cinnabar veins near the Idaho occurrence on Chicken Mountain. These deposits are believed to have formed in low-temperature, epithermal conditions away from the higher temperature Golden Horn and Chicken Mountain plutonic-hosted copper-gold polymetallic systems (Table 3).

Stibnite-gold-quartz veins cut Kuskokwim Group sandstone near the head of the Dishna River, about 45 km north of Chicken Mountain (Fig. 2). This previously unreported occurrence can be traced for about 140 m of strike before disappearing at both ends under Quaternary cover. Open-

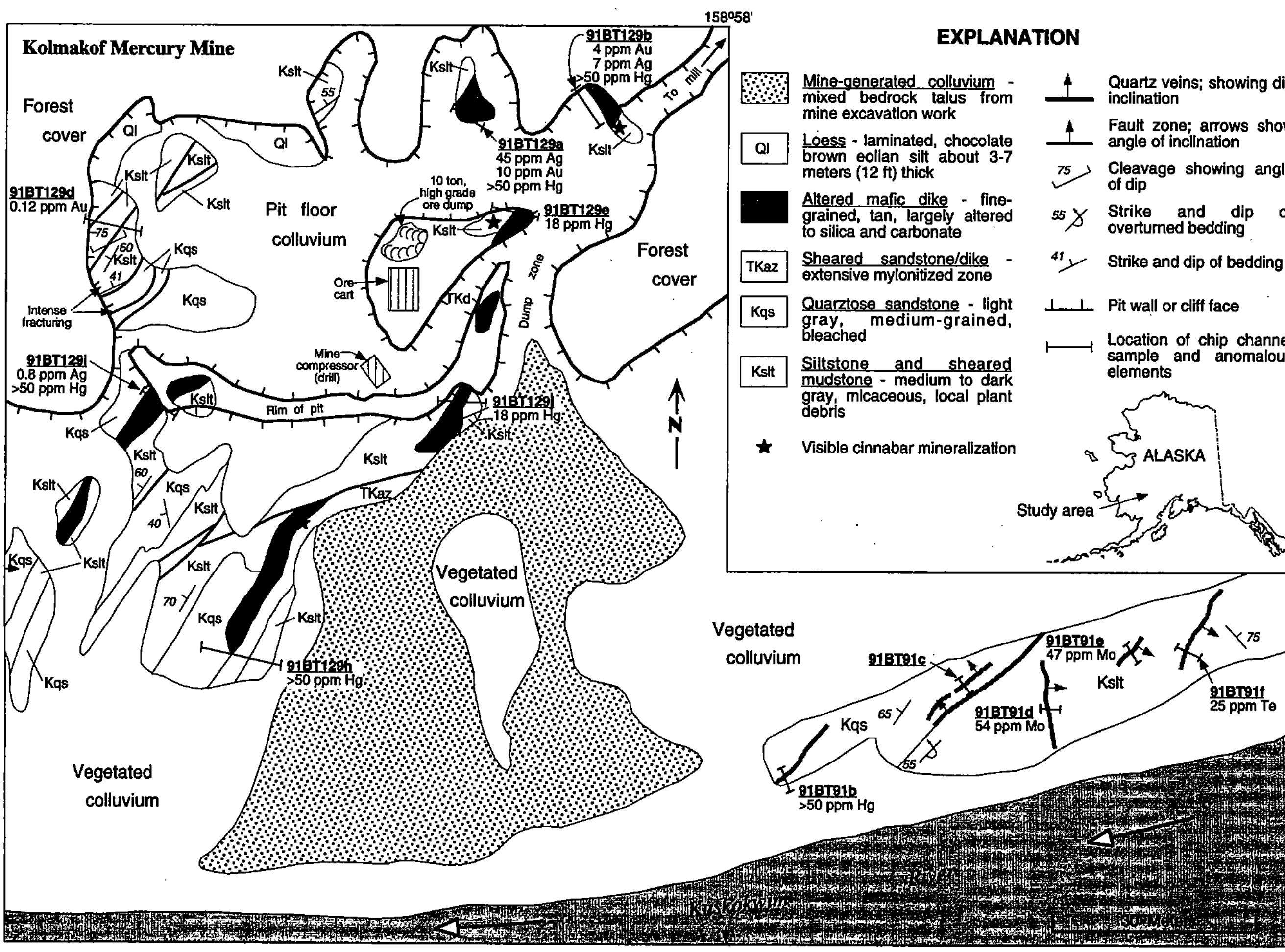


FIG. 17. Geologic sketch of the Kolmakof mercury mine, Sleetmute C-8 quadrangle, illustrating precious metal-bearing mineral zones in a Kuskokwim mercury lode. Data from this study. Sketch by T.K. Bundtzen and G.M. Laird, June 22, 1991.

space texture in quartz, chalcedonic alteration, elevated mercury values (Table 4), and low-temperature dickite alteration near vein contacts suggests this deposit formed under epithermal conditions.

Gold-bearing chalcedonic quartz veins cut Upper Cretaceous Yukon-Koyukuk flysch near the rim of the Poison Creek volcanic field, about 125 km northwest of McGrath (Figs. 1, 2, 18). The auriferous mineralization discovered thus far formed about 2 km from a curvilinear faulted contact between the flysch and andesite tuffs and flows; this contact zone is believed to be the rim of a volcanic caldera, which is composed of ash-flow tuff, siliceous sinter, felsic tuff, andesite tuff, and basaltic andesite (Fig. 18). Grab samples of chalcedonic quartz veins intruding flysch (Fig. 7M) contain up to 3.5 g/t gold, 25 g/t silver, and 1,500 ppm arsenic (authors, unpub. data). The volcanic field yielded a K-Ar whole-rock age of 65.2 Ma (Patton and Moll, 1984).

Gold-silver-bearing samples have been recently found in the Yetna volcanic field (Fig. 2). Values as high as 10 g/t silver, 3 g/t gold, 100 ppm tin, and 500 ppm lead have been reported from chalcedonic breccias, shear zones, and gossan in the Yetna volcanic field (McGimsey et al., 1988). Miller and Bundtzen (1994) reported a K-Ar age date of 60.1 Ma from andesite hosting one of the Yetna volcanic field epithermal Au-Ag occurrences.

Significant epithermal gold-silver mineralization is hosted in altered andesite at Bogus Creek, about 25 km west of the old mining camp of Nyac (Figs. 2, 19). The deposit occurs in Late Cretaceous-early Tertiary andesite that overlies marine andesite and tuff of the Jurassic-aged Nyac terrane. A small, Late Cretaceous quartz monzonite pluton intrudes the Nyac terrane about 4 km southeast of the deposit (Fig. 19). Farther to the east, however, an elongate granitic pluton radiometrically dated as 110 Ma is thought to be the source of placer gold mined in California Creek and probably in the Tuluksak River as well. The Bogus Creek gold-silver prospect consists of stringers and fracture fillings of chalcedonic silica, locally abundant carbonized breccia, and wood chips (Fig. 7N). Plant

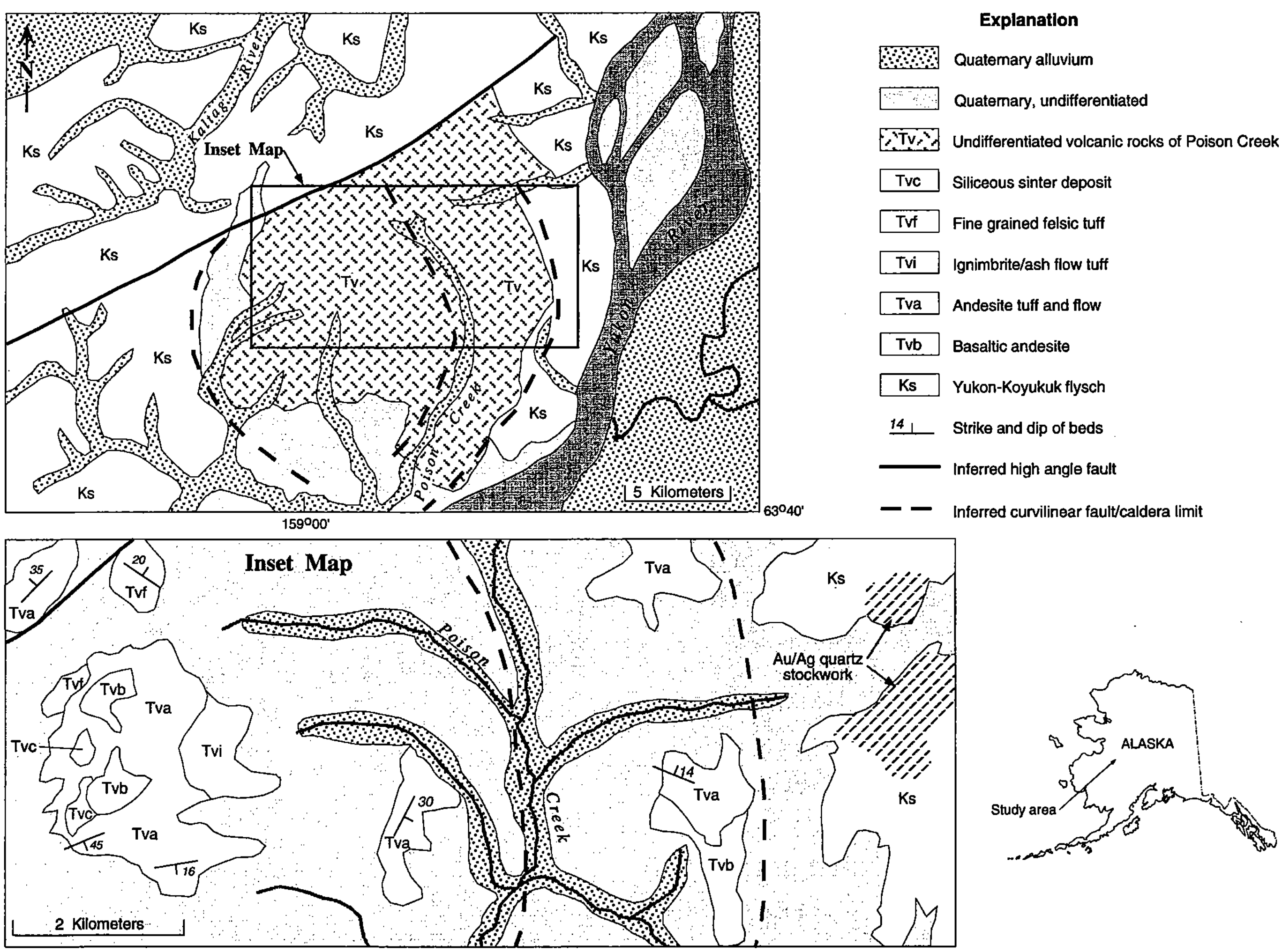


FIG. 18. Geologic sketch of the Poison Creek volcanic field, northern Kuskokwim mineral belt. Inset illustrates relationship of caldera(?) core, rim, and gold-bearing chalcedonic stockwork veins in Cretaceous flysch. Data from Alaska Division of Geological and Geophysical Surveys (1993) and Bundtzen (unpub. data).

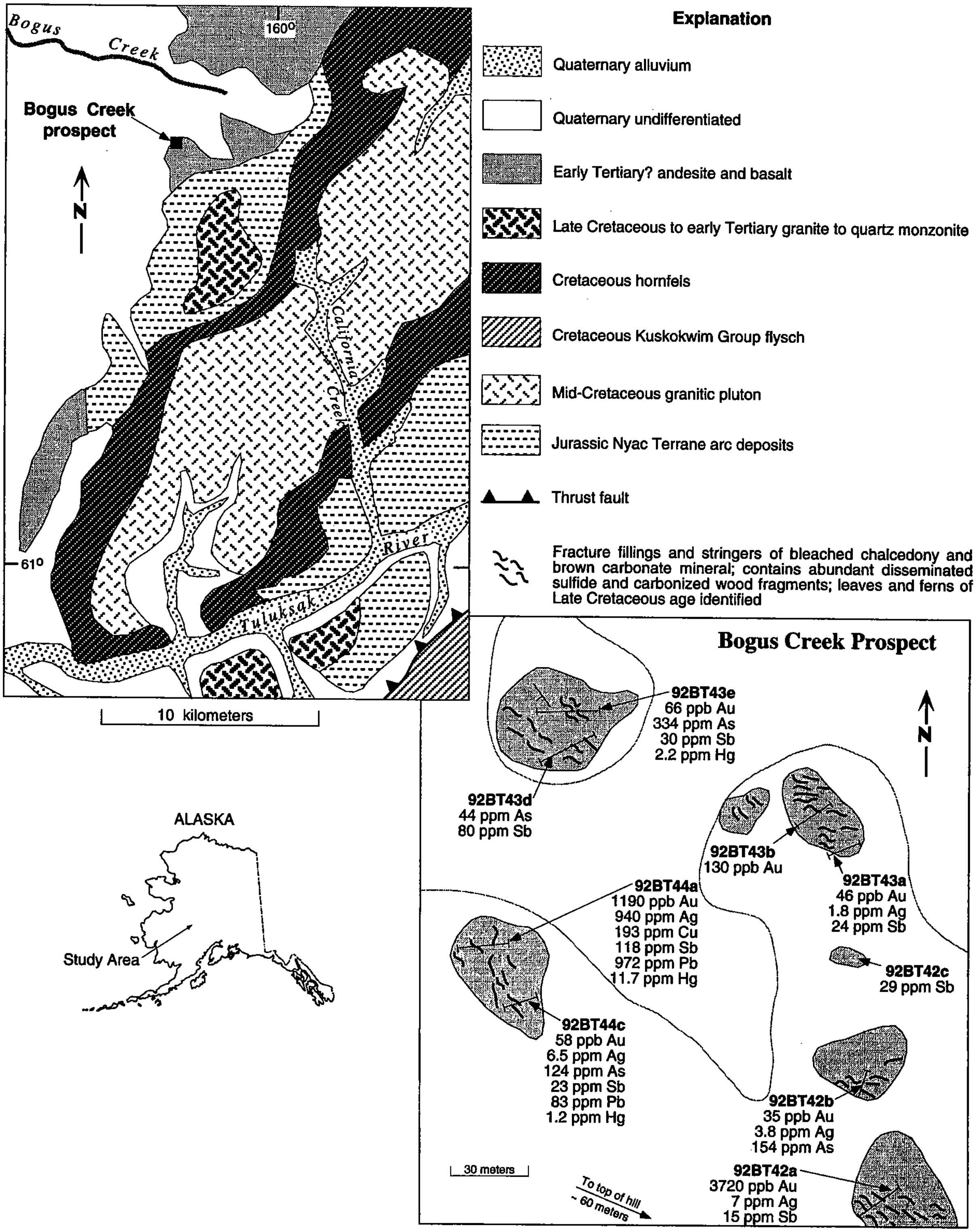


FIG. 19. Geologic sketch of western Aniak-Tuluksak district, Kuskokwim mineral belt, illustrating the style of chalcedonic alteration at the Bogus Creek Au-Ag epithermal system.

fossils discovered by the late Bruce Hickok from chalcedonic breccia at Bogus Creek resemble the Late Cretaceous forms—either *Cladophlebis septentrionalis* or *Nilssoni serotina* (Hollick, 1930)—which suggests that gold-silver-bearing, low-temperature hydrothermal fluids reached surface conditions probably in a hot spring environment. Selected samples in chalcedonically altered shear zones at Bogus Creek run as high as 3.7 g/t Au, 940 g/t Ag, 334 ppm As, 972 ppm Pb, and 118 ppm Sb.

Gold polymetallic heavy mineral placer deposits

The Kuskokwim mineral belt encompasses parts or all of the Marshall-Anvik, Tolstoi, McGrath-McKinley, Innoko, Iditarod, Donlin, Aniak-Tuluksak, Bethel, and Goodnews Bay mining districts (Fig. 1; Ransome and Kerns, 1954; Cobb, 1973). All but 2,140 kg of the total 100,240 kg of gold produced from these districts during the period 1898 to 1995 (Bundtzen et al., 1994, 1996) was recovered from placer deposits (Table 1). Production records from every commercial placer gold deposit in the Kuskokwim mineral belt were examined. Placer gold production has been subdivided according to presumed lode sources, which were identified on the basis of detailed bedrock and surficial geologic mapping in the placer districts, examination of gold fineness and heavy mineral contents from both placer and lode deposits, and positive identification of the four precious metal deposit types described in this paper as being the probable source of the placer gold. Other bedrock sources for placer gold in the study area include Jurassic mafic-ultramafic rocks and middle Cretaceous granitic rocks. When lode sources are ambiguous or believed to originate from more than one bedrock source, the deposit type for the placer gold is considered unknown. We estimate that 61,490 kg of gold, or 63 percent of the total 98,100 kg of placer gold production, was derived from plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits; 20,191 kg of gold, or 20 percent, came from the peraluminous granite-porphyry-hosted gold polymetallic systems; 13,697 kg of gold, or 14 percent, was derived from mineralized, middle Cretaceous plutons in the Bear Creek and Tuluksak River portions of the Aniak-Tuluksak district (which are not described in this paper); and 2,722 kg of gold, or 3 percent, was derived from Jurassic, zoned ultramafic complexes of the Goodnews Bay district, auriferous epithermal systems in volcanic rocks, and unknown sources (Table 6).

Gold-bearing placer deposits formed downslope or downstream from Late Cretaceous-early Tertiary igneous complexes at Nixon Fork, Candle Hills, Vinasale Mountain, the Ganes-Yankee Creek dike swarm, the Ophir-Little Creek dike swarm, Moore Creek, Chicken Mountain, Granite Creek, Donlin Creek, Julian Creek, Bear Creek, Marvel Creek, Marvel Dome, the Cripple Mountains, Wattamuse Creek, Kako Creek, Stuyahok River, and Willow Creek (Fig. 2). Indeed, the exploitation of the placer deposits led to the discovery of lode deposits as well, such as the Golden Horn, Chicken Mountain, Owhat-Headwall-Mission Creek, Nixon Fork, Snow Gulch (Donlin), and Independence (Ganes-Yankee Creek) gold-bearing deposits described above. Bundtzen et al. (1987) utilized suites of specific heavy minerals in concentrates collected in the study area to locate or define the hard-rock sources better for the heavy placer minerals found in the streams. Predictably, these studies showed that heavy minerals found in placer deposits had sources in upslope or upstream lode deposits.

Fineness or purity of the placer gold varies with differing lode sources (Table 7). Placer gold eroded from peraluminous granite-porphyry-hosted gold polymetallic deposits and occurrences in the Innoko, Iditarod (George), Donlin, and Marshall-Anvik districts has fineness values ranging from 654 to 973 and averaging 840 (Table 7). Gold originating in the plutonic-hosted copper-gold polymetallic stockwork and vein deposits in the Tolstoi, McKinley-McGrath, and Iditarod (Flat) districts have a narrower fineness range of 847 to 902. Gold derived from streams draining middle Cretaceous plutons in the Aniak-Tuluksak district have fineness values ranging from 838 to 994 and averaging 933 (Table 7). Trace element analyses and limited electron microprobe data show that placer gold from both plutonic-hosted deposit types contains anomalous As, Cu, Hg, and especially Sb in addition to the typically high silver content common to most placer gold (Bundtzen et al., 1987). Some placer gold from Flat and Otter Creeks, which drain the Chicken Mountain and Golden Horn copper-gold polymetallic stock and vein deposits, contains tiny inclusions of chalcopyrite. Placer gold samples from throughout the Kuskokwim mineral belt contain trace to anomalous mercury values; for example, 10 gold grains from Snow Gulch, in the Donlin district, were found to contain from 3.55 to 8.98 percent mercury, which in some cases actually exceeded the silver content of the bullion (B. Cannon, written commun., 1995).

The combination of trace element content and gold fineness data suggests that gold from both the peraluminous granite-porphyry and plutonic-hosted copper-gold polymetallic stockwork and vein-type deposits formed in conditions spanning the mesothermal to epithermal ranges. High amounts of mercury, antimony, and silver in gold suggest deposition in the epithermal temperature range, whereas a high copper content indicates deposition in the mesothermal temperature range. High-fineness gold, such as the placer gold in the Tolstoi, McKinley-McGrath, and Iditarod (Flat) districts (Table 7), is thought to form in higher temperature conditions (Badalov and Badalova, 1967; Boyle, 1979). Gold fineness data from placer deposits eroding gold-silver epithermal systems in volcanic rocks of the study area are absent.

Bundtzen et al. (1987) detected anomalous platinum metals (437–5,250 ppb PGE) in placer gold from stream drainages at Flat, in the Cripple Mountains, and from Candle Hills, all of which erode Late Cretaceous-early Tertiary, plutonic-hosted copper-gold polymetallic stockwork and vein deposits. It is not known whether the platinum (mainly palladium) occurs as immiscible masses in the crystal lattice of placer gold or as discrete grains in gold. Plutons from these three areas contain wehrlite, alkali gabbro, and monzodiorite intrusive phases (Bundtzen and Laird, 1983b; Miller and Bundtzen, 1994).

Distribution of heavy mineral placers in the study area have been influenced by a variety of conditions, including such structural deformations as vertical movement along faults, stream drainage evolution in a periglacial environment, the relative amount of unroofing of mineralized source rock, and the presence or absence of Pleistocene glaciation (Bundtzen et al., 1985).

Many gold-bearing alluvial terraces found in the Kuskokwim mineral belt and throughout interior and western Alaska are relict stream drainages that began to form in Miocene to Pliocene time (Hopkins et al., 1971). An asymmetrical

TABLE 6. Summary of Gold-Silver Polymetallic Mineral Deposit Types from Late Cretaceous-Early Tertiary Igneous Complexes, Kuskokwim Mineral Belt, Southwest Alaska

Deposit type	Geology of host rocks	Plutonic-volcanic compositions	Mineralogy of ore	Structure, morphology	Alteration	Remarks
1. Plutonic-hosted copper-gold-polymetallic stockwork-vein (skarn)	Volcanic-plutonic complexes intrude Kuskokwim Group and Nukluk terrane; some plutons intrude Paleozoic limestone	Heterogeneous and variable, from alkali gabbro to granite; many average monzonite; generally meta-aluminous and range from 40 to 67% SiO_2; contains elevated Th and U; generally reduced (ferric/ferrous ratio) conditions	Deeper levels contain chalcopyrite, molybdenite, scheelite, and arsenopyrite; upper levels contain Ag-Sb sulfosalts, arsenites, stibnite, free gold; oxidized skarns contain cuprite and malachite protore rich in bornite and chalcopyrite	Vertically zoned systems in intrusive stockworks, minor stockwork in hornfels cap and overlying volcanics; mesothermal T-P conditions at depth; epithermal T-P conditions at higher levels; cupola zones are best targets for gold; structural zones in exoskarn near pluton best target for skarn deposits	Ankerite, potassic, propylitic (chlorite-epidote), and silicic alteration; no clear patterns developed in most mineralized plutons; early pyroxene magnetite-garnet, later wollastonite in skarn types	Accounts for 25,980 kg gold, or 16% of known lode gold resources in the Kuskokwim mineral belt
2. Peraluminous granite-prophyry-hosted gold-polymetallic	Granite-porphyry dikes and sills that give way to shallow intrusions	Several varieties of peraluminous alaskite to alkalic granite, frequently contains garnet; heavy REE depletion trends; possible product of crustal melting; both oxidized and reduced intrusions present	Stibnite, cinnabar, arsenopyrite, Sb sulfosalt	Generally high-level emplacement along high-angle faults (Ganes-Yankee and Donlin faults): orebodies are distinct lenses in both porphyry and host rocks	Argillic, potassic, and silicic alteration plus dickite	Accounts for 136,500 kg gold, or 84% of known lode gold resources in Kuskokwim mineral belt
3. Plutonic-related boron-enriched silver-tin-polymetallic greisen and vein deposits	Hosted in hornfels sedimentary rock, volcanic rocks, and high-level plutonic rocks; usually a component of volcanic-plutonic complexes, which intrude Kuskokwim Group flysch	Meta-aluminous to peraluminous; undersaturated, reduced plutons of two ages: 65n70 and 58–62 Ma; the younger ages predominate; fewer intrusive phases than type 1 above.	Cassiterite, Sb-Ag sulfosalts, chalcopyrite, salena; abundant tourmaline, quartz, axinite gangue minerals	Veins, stockworks, and replacements	Strong boron metasomatism; silicic alteration in intrusion-hosted types; axinite-tourmaline veins and stockwork in hornfels	Recently recognized deposit type; potentially large silver resources may be zoned part of deposit type 1 above
4. Epithermal gold-silver systems	Highly variable: (1) associated with altered mafic dikes; (2) distal to stockwork deposit types above; (3) chalcedonic veins and stockwork zones in host rocks	(1) Highly altered olivine basalt; (2) meta-aluminous; reduced, monozonite to granitic plutons; (3) calc-alkalic andesite to rhyolite volcanic host rocks	(1) Cinnabar, stibnite, free gold; (2) cinnabar, stibnite, arsenates, Ag sulfosalts; (3) sulfosalts, cinnabar	High-level systems in all cases: (1) introduction along faults; (2) as distal zones to porphyry or vein type Ag-Au polymetallic deposits; (3) as ring structures distal to volcanic calderas	(1) Silica-carbonate and dickite; (2) potassic, phyllic; (3) chalcedonic, adularia	Poorest understood of all gold-silver resources of study area; accounts for <1% of known gold resources in Kuskokwim mineral belt
5. Heavy mineral placer deposits	Stream, colluvial, and residual accumulations derived from erosion of mineral deposit types listed above	All deposit types listed above have generated heavy mineral gold placers in Kuskokwim mineral belt	Free gold, electrum, cinnabar, stibnite, ilmenite, magnesiochromite, cassiterite, monazite, garnet, edenite, richterite, scheelite, radioactive zircon, ilmenorutile, trace platinum-group elements	Residual or colluvial deposits develop on grussified mineralized intrusions and in dike swarms; fluvial placers found in both ancestral and modern stream gravels; best deposits occur in third-order streams; richness dependent on age and reconcentration processes	NA	Lode sources for 98,100 kg placer gold mined in Kuskokwim mineral belt (1990–1995) derived as follows: plutonic-hosted Cu-Au stockwork and vein, 61,490 kg (63%); peraluminous granite-porphyry Au-polymetallic, 20,191 kg (20%); middle Cretaceous plutons, 13,697 kg (14%); all other types, 2,722 kg (3%)

NA = not available

TABLE 7. Summary of Heavy Mineral Placer Data from Selected Portions of the Kuskokwim Mineral Belt

District[1]	Geology of presumed lode source	Gold fineness[2]	Major and minor heavy minerals	Anomalies, remarks
Tolstoi	Late Cretaceous-early Tertiary, meta-aluminous, alkali-calcic to quartz alkalic plutons of monzonitic composition	864–902; avg = 897	Zircon, magnetite, ilmenite, samarskite, powellite, xanthoconite, cassiterite	Platinum in gold bullion at Colorado Creek; anomalous tin, niobium, molybdenum, and uranium; silver sulfides
Innoko	Bimodal dike swarms; gold mainly from peraluminous granite-porphyry, with contribution from alkali-calcic monzonite on Yankee Creek; both intrusive suites are of Late Cretaceous-early Tertiary age	846–898; avg = 853	Magnetite, cinnabar, chromite or magnesio-chromite, scheelite, monazite, ilmenorutile, native silver, platinum	Scheelite very abundant in Little Creek; platinum from Boob Creek probably derived from Jurassic ophiolite
McKinley-McGrath	Meta-aluminous, quartz alkalic monzonitic plutons in Candle Hills; all of Late Cretaceous-early Tertiary age	894–902; avg = 898	Magnetite, magnesio-chromite, cinnabar, olivine, ilmenorutile, sodic amphibole, scheelite, platinum	Anomalous platinum in gold bullion; niobium end member in ilmenorutile
Iditarod (Moore)	Meta-aluminous, alkalic-calic boron-enriched plutons of monzonitic composition; Late Cretaceous-early Tertiary age	758–883; avg = 836	Chromite, cinnabar, native silver, silver sulfosalts	Highest silver/gold ratio of any district
Iditarod (George)	Both meta-aluminous, alkalic calcic monzonite and peraluminous granite-porphyry (very similar to Innoko-Ophir); both suites of Late Cretaceous-early Tertiary age	835–857; avg = 853	Magnetite, garnet, cinnabar, stibnite, monazite	Julian Creek has most radioactive concentrates of all examined
Iditarod (Flat)	Meta-aluminous, quartz alkalic gabbro to monzonite plutons of Late Cretaceous-early Tertiary age	847–874; avg = 867	Cinnabar, chromite, arsenopyrite, pyrite, zircon, cinnabar, ilmenorutile, scheelite, cassiterite	Anomalous platinum in gold bullion; uranium in zircon; scheelite and cinnabar very abundant in Otter Creek drainage
Donlin	Peraluminous granite-porphyry dikes of Late Cretaceous-early Tertiary age	802–901; avg = 837	Garnet, cassiterite, stibnite, monazite, cinnabar	Radioactive concentrates similar to Julian Creek; mercury content in selected gold grains from Snow Gulch ranges from 3.55 to 8.98%
Aniak-Tuluksak	Mineralized middle Cretaceous pluton is probable source of about 70% of placer gold; remainder derived from Late Cretaceous-early Tertiary plutons and epithermal veins	838–994; avg = 933	Stibnite, cinnabar, megnetite, cassiterite, chalcopyrite	Gold from Bear Creek contains minor intergrowths of chalcopyrite; Spruce Creek gold contains gold telluride calaverite and inclusions of rutile in gold
Bethel	Veins in monzonite to granodiorite plutons of Late Cretaceous-early Tertiary age	avg = 875	Cinnabar, zircon, ilmenorutile	Gold from Eureka Creek contains aurostibite (AuSb) and bismuth sulfosalts
Marshall-Anvik	Peraluminous, granite-porphyry dikes, sill, and small plutons intrude Lower Cretaceous (Neocomian) volcanic and volcaniclastic rocks of Yukon-Koyukuk terrane	654–973; avg = 817	Cinnabar, stibnite, arsenopyrite, pyrite, monazite	Gold grains from Flat Creek show intricate vermicular sunburst muscovite inclusions

[1] District locations shown in Figure 1

[2] Fineness data from Smith (1941), Bundtzen et al. (1987), and this study

valley, one in which opposing valley sides have markedly different slope angles, is the characteristic stream profile in the Kuskokwim mineral belt. The steep walls of asymmetrical valleys face north or east, whereas the gentle slopes face south or west. This asymmetry is considered normal (Melton, 1960) and is probably the result of greater solifluction activity resulting from greater thermal exposure on south or southwest slopes. In contrast, the steeper valley slopes on the north or east receive less sunlight and are frequently frozen. As a result, the permafrost thaws differentially, and colluvial materials move down the south- or west-facing slopes and advance toward east- or north-facing frozen buttresses. This process forces perennial streams to migrate south or west, creating active channels against the steep valley walls. During migration, the stream leaves a successive series of older alluvial terraces. Many placer gold-bearing drainages in the Kuskokwim mineral belt evolved in this fashion. Of the estimated 78 gold placer deposits known in the Kuskokwim mineral belt, 62 of the valleys (or 84%) exhibit valley asymmetry showing gentle west- or south-facing slopes, 8 (11%) exhibit valley asymmetry showing gentle east- or north-facing slopes, and 4 (5%) exhibit no pronounced valley asymmetry at all. Figure 20 illustrates the placer gold deposits and normal valley asymmetry of Spruce Creek, in the Innoko district.

Reconcentration cycles seem to be important local features of placer deposits in the Kuskokwim mineral belt, and third-order streams seem to have produced the richest placer gold deposits. In the Donlin district, economic quantities of placer gold are restricted to zones where modern stream gulches intersect the auriferous (but subeconomic) Donlin bench, an ancestral drainage of Donlin Creek (Fig. 11). Donlin Creek originally flowed northeast into the Iditarod River, which eventually drains into the Yukon River basin; after regional tilting, the drainage reversed direction and flowed into the Kuskokwim River basin. Enriched placer gold occurs where younger streams and gulches cut and reconcentrate gold derived from the older Donlin Bench gravel deposits.

Modern stream, alluvial terrace, colluvial, and residual placer deposits have all been exploited in the study area but are particularly well developed in the Iditarod-Flat district. Bundtzen et al. (1992) have described a progressive evolution from residual to eluvial to stream heavy mineral placer development as a result of progressive erosion of plutonic-hosted copper-gold polymetallic stockwork and vein deposits on Chicken Mountain and in Black Creek from the late Tertiary to the present (Figs. 2, 9). High-grade paystreaks on the Willow bench, an ancestral stream of Willow Creek, are found where younger streams intersect the older auriferous terrace alluvium; the geomorphological setting of Willow Creek is analogous to reconcentration processes observed at Donlin Creek, described above.

In both the Ophir and Ganes-Yankee Creek areas of the Innoko district (Figs. 2, 12, 13), gold polymetallic placer deposits occur in both ancestral (Tertiary?) terraces and younger, Pleistocene-age stream gravels. The placers formed during multiple periods of erosion and reconcentration of gold derived from mineralized, peraluminous granite-porphyry dikes, sills, and stocks.

Placer gold has been found in small quantities in the Beaver, Russian, and Horn Mountains, all of which contain gold-bearing vein-type mineralization (Fig. 2). However, no commercial placer gold production has ever taken place in these areas. All three mountain ranges have undergone at least four periods of Pleistocene glaciation, ranging from early Pleistocene to early Holocene (Kline and Bundtzen, 1986). Glacial activity frequently disperses, buries, or removes heavy mineral placer concentrations deposited by streams. For example, about 75 percent of placer gold mined in Alaska and nearly 80 percent of placer gold recovered in Yukon Territory, Canada, have come from areas that either were never glaciated or were subjected to erosion and concentration processes during interglacial periods (Bundtzen, 1980; Morison, 1990). In the latter case (i.e., the Valdez Creek mine in south-central Alaska), placer deposits were subsequently preserved through burial by younger glaciofluvial deposits (Reger and Bundtzen, 1990).

Placer deposits throughout the Kuskokwim mineral belt are from 1 to 20 m thick and contain from less than 0.5 to 15 g/t gold, averaging about 0.8 g/t gold. Scheelite and cinnabar have been recovered as commercial by-products from placer gold deposits in the Innoko, McGrath-McKinley, and Iditarod-Flat districts (Figs. 1, 2). All the placer gold deposits of the study area have yielded by-product silver (Table 1).

Metallogenic Model and Discussion

Figure 21 and Table 6 compare the four precious metal-bearing lode mineral deposit types and placer deposits associated with Late Cretaceous-early Tertiary igneous rocks of the Kuskokwim mineral belt. The detailed geology, trace element geochemistry, ore mineralogy, and ore paragenesis discussed earlier in this paper indicate that the lode types span the hypothermal(?), mesothermal, and epithermal temperature and pressure conditions. Data from these studies, coupled with exploration drilling by private firms, support the contention that vertical and lateral mineral zonation occurs in precious metal-bearing systems throughout the study area. Higher temperature-pressure (mesothermal to hypothermal[?]) deposits occur at deeper structural levels and at lower temperature-pressure mineral assemblages formed in lower mesothermal and epithermal conditions. The mineral deposits related to Late Cretaceous-early Tertiary igneous complexes throughout the Kuskokwim mineral belt represent similar, if not the same, zoned hydrothermal systems now exposed at several erosional levels.

Plutonic-hosted copper-gold polymetallic deposits in the Russian Mountains and in the Iditarod-Flat district contain temperature-pressure mineralization in the upper mesothermal or hypothermal(?) range. Geothermometry data on arsenopyrite summarized by Bundtzen and Laird (1991) indicate that gold-bearing arsenopyrite from the Owhat deposit in the Russian Mountains crystallized at 320°C. Deep levels of the Chicken Mountain and Golden Horn deposits show initial mineralizing events containing deuteric-magmatic muscovite-biotite-quartz alteration and decrepitation temperatures from quartz of 387° and 401°C, respectively (Table 5).

Plutonic-hosted copper-gold polymetallic, plutonic-related boron-enriched silver-tin polymetallic, and peraluminous granite-porphyry-hosted gold polymetallic deposits were probably deposited in the lower to middle mesothermal ranges. Second, third, and fourth mineralizing events in the

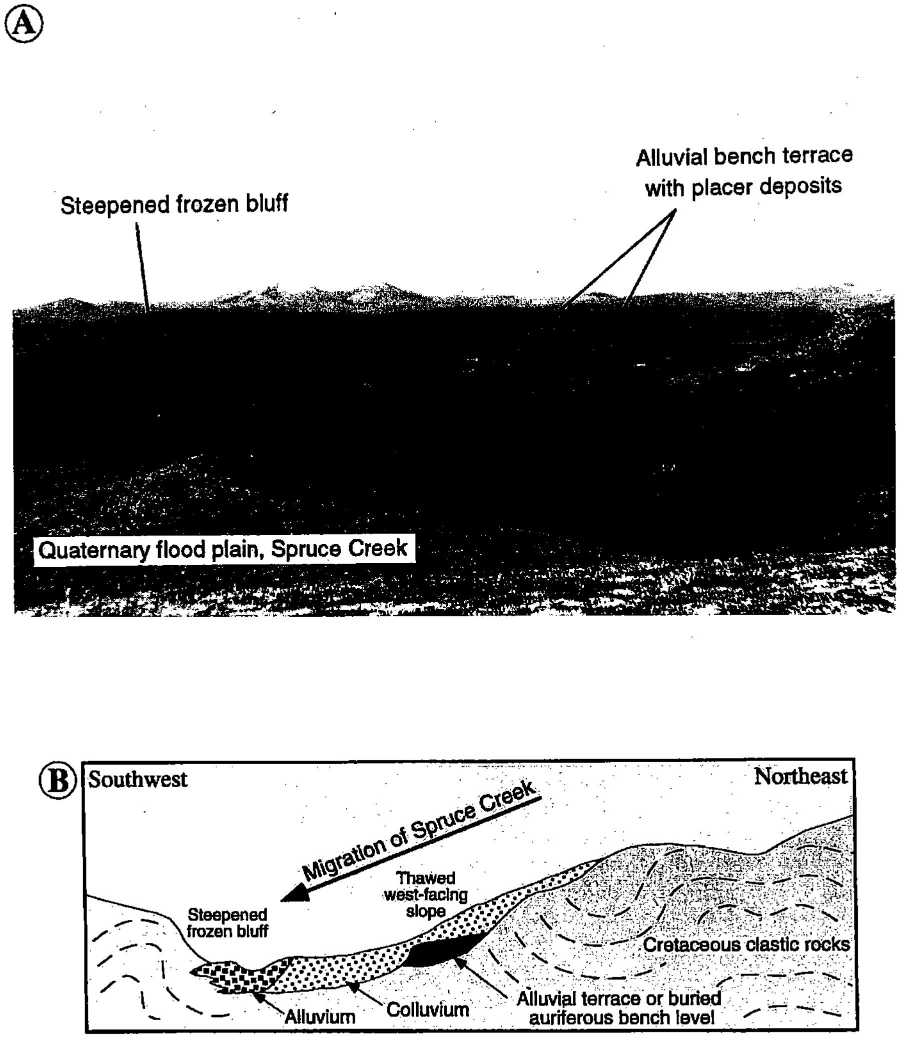


FIG. 20. Asymmetrical valley formation in the Kuskokwim mineral belt and its influence on gold placer deposits. Example depicted here is the Spruce Creek placer deposit, in the Innoko district.

Chicken Mountain and Golden Horn deposits that deposited copper, gold, arsenic, silver, and lead minerals show homogenization temperatures of 148° to 239°C from fluid inclusions in quartz gangue (Table 5). Bull (1988) estimated that the mineralized Chicken Mountain pluton was emplaced at 1.0 to 1.5 kbars or in shallow epizonal conditions, based on plotting feldspar crystallization temperatures on a granite minimum curve.

Homogenization temperatures of quartz fluid inclusions from the Broken Shovel deposit near Moore Creek, which is interpreted in this paper as a boron-enriched silver-tin polymetallic deposit type, range from 254° to 380°C and average 297°C (Bundtzen et al., 1988).

No homogenization temperatures from peraluminous granite-porphyry-hosted gold polymetallic deposits exist from the study area. A mesothermal classification is based primarily on textural relationships and mineral assemblages. Muscovite (in contrast to sericite) alteration, more typical of mesothermal altered zones in porphyry deposits, has been recognized in almost all deposits. Arsenopyrite, pyrite, stibnite, and silver sulfosalts thought to be associated with lower mesothermal mineralization occur in most deposits. Alteration zones generally lack chalcedony and adularia, typically associated with epithermal systems. Retherford and McAtee (1994) reported, however, that the Donlin deposit(s) formed in epithermal conditions, citing (1) close spatial association with cinnabar mineralization, (2) illite alteration, and (3) low-temperature clay minerals associated with quartz sulfide breccia veins. They further speculated that copper porphyry-type mineralization lies below the main Donlin gold polymetallic deposits, based on the presence of higher temperature muscovite and base metal-bearing veins encountered at depth. Selected gold grains from Donlin Creek placer deposits contains from 3.55 to 8.98 percent mercury, which illustrates the high mercury content in the Donlin Creek mineral deposits. The Rhyolite mercury deposit, which probably formed in epithermal conditions, is hosted in the same peraluminous granite-porphyry dike and sill swarm as the Donlin deposit(s). It is likely that

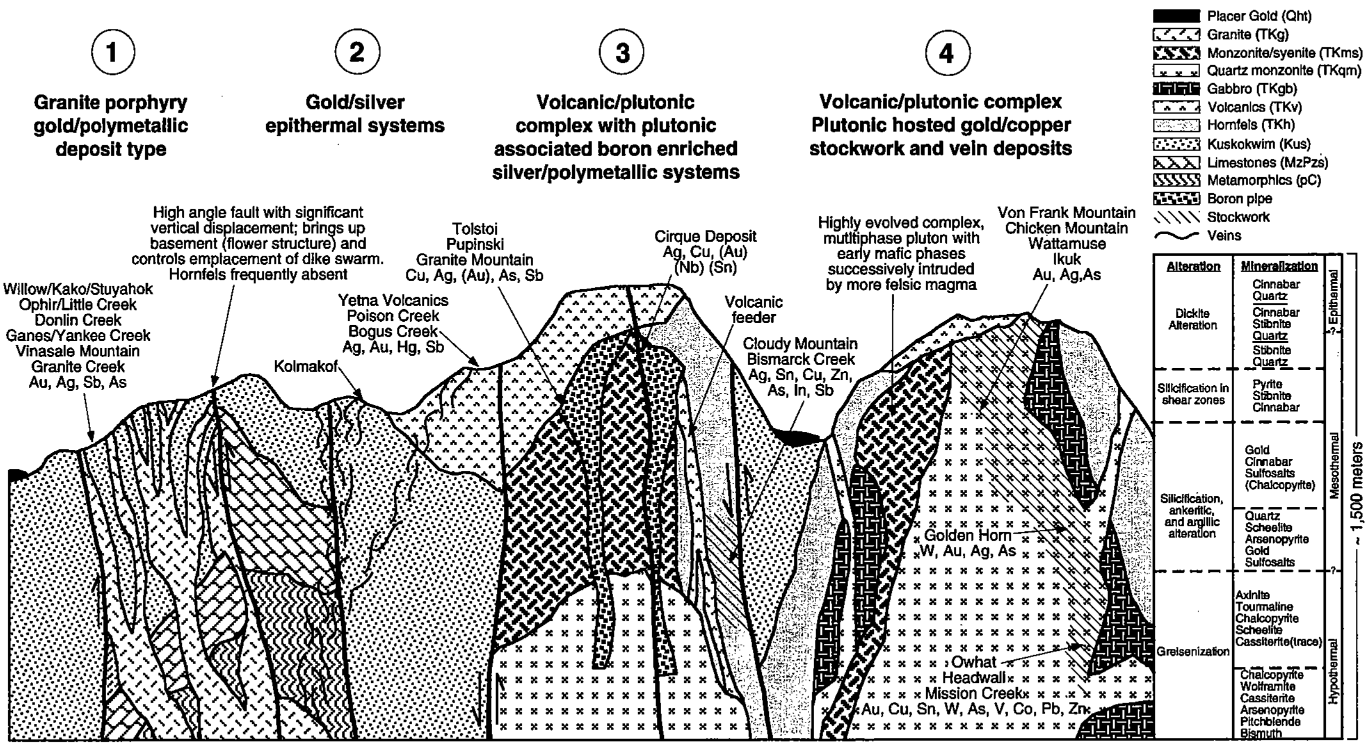


FIG. 21. A composite metallogenic model for gold-silver polymetallic mineralization in the Kuskokwim mineral belt of southwest Alaska, depicting four styles of mineralization: (1) peraluminous granite-porphyry gold polymetallic deposits and associated high-level dike swarms; (2) gold-silver in epithermal systems associated with volcanism and hot spring environments; (3) plutonic-related, boron-enriched silver-tin polymetallic systems associated with tourmaline breccia pipes and base metal porphyry systems; and (4) plutonic-hosted copper-gold polymetallic stockworks and veins, probably alkalic copper-gold systems.

peraluminous granite-porphyry-hosted gold polymetallic deposits in the study area formed in conditions spanning the mesothermal and epithermal ranges.

Gold-silver deposits associated with altered mafic dikes, andesitic calderas, or volcanic fields, or those distal to plutonic-hosted copper-gold polymetallic stockwork and vein deposits, formed in low-temperature, low-pressure epithermal conditions. Fluid inclusions from spatially related mercury-antimony deposits formed in the range of 160° to 210°C and under 150 to 1,500 bars (Miller et al., 1989; Gray et al., 1992). Chalcedonic (+ adularia) alteration occurs in the DeCourcy Mountain, Bogus Creek, Poison Creek, and Kolmakof deposits discussed earlier.

Determining absolute ages of precious metal-bearing deposits associated with Late Cretaceous-early Tertiary igneous complexes is hampered by the sparsity of isotopic age data, and in many instances, the mineralization age of a specific deposit is inferred from the isotopic age of genetically related igneous rocks. However, nine isotopic mineral ages from six deposits have been completed in the study area. Hydrothermal sericite from the Ophir-Little Creek peraluminous granite-porphyry-hosted gold polymetallic prospect yielded a K-Ar age of 70.1 Ma, which is, within analytical error, the same age as the 71.2 Ma age determined on primary igneous muscovite in the dike swarm near Ophir. DiMarchi (1993) obtained a K-Ar date of 68.0 Ma from hydrothermal sericite and a fission track age of 69.0 Ma from apatite from the central zone at the Vinasale Mountain granite-porphyry gold polymetallic deposit. He also reported fission track ages of 73.0 and 69.0 Ma from the northeast mineral zone on Vinasale Mountain; within analytical error, all ages are the same as crystallization ages obtained from the pluton, which are 68.1 and 69.0 Ma (Bundtzen, 1986; DiMarchi, 1993). Epithermal mercury-antimony deposits at the DeCourcy Mountain, Fairview, and Rhyolite deposits have yielded K-Ar and $^{40}Ar/^{39}Ar$ ages of 76.0, 72.5, and 72.0 Ma, respectively. All are similar to the ages of nearby intrusive bodies and volcanic fields, which have been radiometrically dated to range from 65 to 74 Ma at DeCourcy Mountain, Barometer Mountain, and in the Horn Mountains. Secondary(?) biotite from the Black Creek pluton that might date mineralizing events of the Golden Horn copper-gold polymetallic stockwork and vein deposit, yielded a K-Ar isotopic age of 63.4 Ma, which is the youngest mineralization age in the belt. We have no isotopic ages from boron-enriched silver-tin polymetallic deposits in the study area. Host plutons for this deposit type range in age from 70.9 to 59.4 Ma, and three of the deposits are associated with plutons whose isotopic ages range from 63 to 59 Ma.

With the exception of the isotopic age from the Golden Horn deposit, all available mineralization ages cluster in the range between 76 and 68 Ma. The available data, although sparse, seem to indicate that mineral deposits and Late Cretaceous-early Tertiary igneous complexes in the Kuskokwim

TABLE 8. Sulfur Isotope Analyses from Late Cretaceous-Early Tertiary Sulfide-Bearing Mineral Deposits in the Kuskokwim Mineral Belt, Alaska

Sample no.	Ore deposit name	Mineral deposit type	Mineral	$\delta^{34}S$ (0/00)
84BT102c	Chicken Mountain	Plutonic-hosted copper-gold-polymetallic	Antimony sulfosalt	−6.5
88BT67b	Owhat	Plutonic-hosted copper-gold-polymetallic	Arsenopyrite	−6.3
82BT201a	Vinasale	Peraluminous granite-porphyry-hosted gold-polymetallic	Sphalerite	0.8
82BT201b	Vinasale	Peraluminous granite-porphyry-hosted gold-polymetallic	Pyrite	0.9
79BT441a	Tolstoi	Plutonic-related, boron-enriched silver-tin-polymetallic	Chalcopyrite	−3.4
79BT441b	Tolstoi	Plutonic-related, boron-enriched silver-tin-polymetallic	Chalcopyrite	−4.1
81BT501	Cirque	Plutonic-related, boron-enriched silver-tin-polymetallic	Chalcopyrite	−3.3
84BT34	Bismarck Creek	Plutonic-related, boron-enriched silver-tin-polymetallic	Sphalerite	−2.5
84BT34	Bismarck Creek	Plutonic-related, boron-enriched silver-tin-polymetallic	Galena	−1.3
91BT420a	Kolmakof	Epithermal gold-silver	Cinnabar	−3.9
91BT420b	Kolmakof	Epithermal gold-silver	Cinnabar	−4.7
88BT601	Red Devil	Epithermal gold-silver	Cinnabar	−4.2
86BT365	Dishna River	Epithermal gold-silver	Stibnite	−6.2

Analyses by Krueger Enterprises, Incl; $\delta^{34}S_{sample}$ ‰ $= \frac{^{34}S/^{32}S \text{ sample}}{^{34}S/^{32}S \text{ standard}} - 1 \times 1{,}000$; standard is Canyon Diablo troilite

mineral belt, as summarized in this paper, are about the same age. Additional isotopic age data should be collected to date all deposit types, especially the plutonic-related, boron-enriched silver-tin polymetallic deposit type.

Table 8 summarizes sulfur isotope data from nine mineral deposits representative of the four lode deposit types discussed in this paper. The sulfide minerals have relatively light $\delta^{34}S$ values that range from −6.5 to -0.9 per mil and average −3.4 per mil, which contrasts with heavier $\delta^{34}S$ values from plutonic-related deposits of Cretaceous age in the Fairbanks and Kantishna districts of interior Alaska (Gilbert and Bundtzen, 1979; Metz, 1991; T.K. Bundtzen unpub. data). The lightest $\delta^{34}S$ values are associated with the plutonic-hosted copper-gold polymetallic (avg −6.4‰) and gold-silver epithermal (avg −4.8‰) deposit types. Samples from the Tolstoi, Cirque, and Bismarck Creek plutonic-related, boron-enriched silver-tin polymetallic deposits yielded slightly heavier $\delta^{34}S$ values that average −2.9 per mil. Ishihara et al. (1992, 1995) reported that similar light sulfur isotope analyses from mineral deposits in the Okhotsk-Chukotka mineral belt of the Russian northeast and the Sanyo and Ryoke mineral belts of northern Japan are the result of metallogenic processes associated with reduced, ilmenite series plutons of Mesozoic-Tertiary age. This interpretation would be consistent with our observations that many precious metal-bearing plutons of the Kuskokwim mineral belt exhibit reduced (ilmenite series) characteristics (see Fig. 6).

In contrast, sulfides from the Vinasale peraluminous granite-porphyry-hosted gold polymetallic deposit yielded the heaviest $\delta^{34}S$ values (0.8 and 0.9‰; Table 8). The Vinasale, Donlin, Ganes-Yankee, and other precious metal-bearing granite-porphyry dike and sill swarms in the study area exhibit a high oxidation state (Fig. 6). Their heavier $\delta^{34}S$ values and oxidized character reinforce our contention that the peraluminous granite-porphyry-hosted gold polymetallic deposit type is distinct from others described in this paper.

Lead isotope values obtained from galenas at 16 mineral deposits in the Kuskokwim mineral belt (Gaccetta and Church, 1989; this study) are distinctly less radiogenic than those from samples associated with subduction-related plutons of Cretaceous-Tertiary age in the western United States (Fig. 22). Only galena from the Nixon Fork skarn deposit plots in the intrinsic, plutonic-related deposit field, as defined by Newberry et al. (1995). Galenas from the remaining deposits of the Kuskokwim mineral belt plot in the field of mixed origin deposits, for which Newberry et al. (1995) attribute both plutonic and metamorphic fluid involvement in the mineralizing process. However, we envision little if any metamorphic fluid involvement in the formation of Kuskokwim mineral belt lodes. The less radiogenic lead values from the Kuskokwim deposits may reflect the alkalic component of many Kuskokwim mineral belt plutons and the possible contribution of mantle to their origin (Newberry and Brew, 1993).

Overall characteristics of three of the four precious metal-bearing lode deposits described in this paper resemble those of published ore deposit models. The plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits conform to deposit models 20c (porphyry Cu-Au; Cox, 1986b), 18b (Cu skarn; Cox and Theodore, 1986), and 22c (polymetallic veins; Cox, 1986a). The plutonic-related, boron-enriched silver-tin polymetallic deposits best conform to deposit models 20a (porphyry Sn; Reed, 1986) and 20b (Sn polymetallic; Togashi, 1986). The three gold-silver deposit subtypes associated with epithermal systems likely correlate with deposit models 25a (hot spring Au-Ag; Berger, 1986), 25b (Creede epithermal veins; Mosier et al., 1986b), and 25d (Sado epithermal veins; Mosier et al., 1986a).

The relationship between the plutonic-hosted copper-gold polymetallic vein, skarn, and stockwork deposits and the plutonic-related, boron-enriched silver-tin polymetallic deposits of the Kuskokwim mineral belt is uncertain. High silver/gold ratios; anomalous tin, bismuth, zinc, indium, and lead values; morphology; and boron metasomatism characterize the latter deposit type, whereas low silver/gold ratios; high arsenic, copper, molybdenum, and antimony; and little or no boron metasomatism characterize the former. Plutons hosting the boron-enriched silver-tin polymetallic deposits at Granite Mountain, Tatalina Mountain, and Bismarck Creek have distinctly younger ages and are within the same age range as the Sleitat tin-tungsten deposit in the Taylor Mountains quadrangle

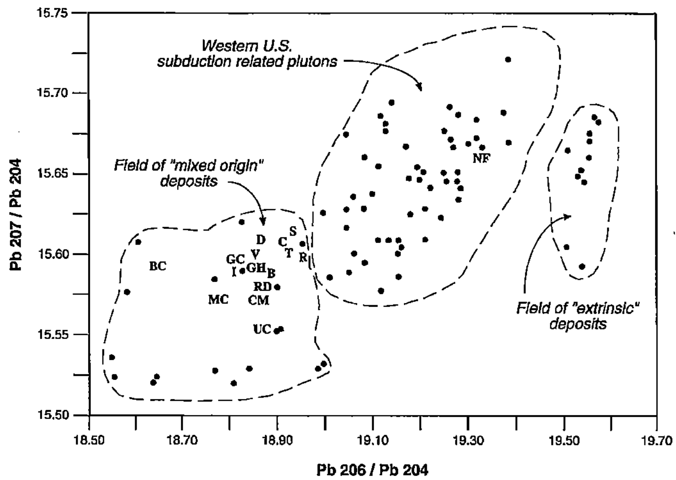


FIG. 22. Lead isotope ratios for galenas from precious metal-bearing deposits in the Kuskokwim mineral belt of southwest Alaska. Data mainly from Gaccetta and Church (1989) and this study. BC (Beaver Creek), CM (Chicken Mountain), GH (Golden Horn), and NF (Nixon Fork) are plutonic-hosted copper-gold polymetallic deposits; GC (Granite Creek), I (Independence), S (Snow Gulch), and V (Vinasale Mountain) are peraluminous granite-porphyry-hosted gold polymetallic deposits; C (Cirque), B (Broken Shovel), MC (Mission Creek), T (Tolstoi), and UC (Upper Cirque) are plutonic-related, boron-enriched silver-tin polymetallic deposits; D (DeCourcy Mountain), R (Rhyolite), and RD (Red Devil) are gold-silver deposits associated with epithermal systems. Field for Cretaceous-Tertiary subduction-related plutons in the western United States from Zartman (1974) and Newberry et al. (1995); fields for extrinsic (nonpluton-related) and mixed origin (plutonic and metamorphic) deposits after Newberry et al. (1995).

(Burleigh, 1991). However, the lode deposits in the Russian Mountains have characteristics of both deposit types. They carry high bismuth and tin and show boron metasomatism characteristic of the boron-enriched silver-tin polymetallic type, but they have low silver/gold ratios, elevated uranium and thorium, and low zinc values, which are characteristic of the plutonic-hosted copper-gold polymetallic deposit type. The Nixon Fork pluton hosts both skarns (the Nixon Fork mine) that correlate with the plutonic-hosted copper-gold polymetallic deposit type and a structurally controlled silver-tin-copper deposit (Pupinski), which is thought to be the boron-enriched silver-tin polymetallic deposit type. Detailed studies by Szumigala (1995) of mineral occurrences in the Beaver Mountains, which have been classified as the boron-enriched silver-tin polymetallic type in this paper, show that fluid inclusions are usually small, liquid rich, and NaCl poor and contain slight amounts of vapor and no daughter products. Fluid inclusions in most porphyry systems usually contain high salinities, evidence of double boiling, and daughter crystals (Roedder, 1984); hence a key line of evidence linking Beaver Mountains mineralization (such as the Cirque and Tolstoi deposits) to porphyry copper-gold systems is missing.

Classification of the peraluminous granite-porphyry-hosted gold polymetallic deposits of the Kuskokwim mineral belt is problematical. Copper is usually absent in the granite-porphyry-hosted gold polymetallic deposits of the study area, whereas gold-bearing porphyry models described in Cox and Singer (1986) and by Laznicka (1985) usually contain substantial copper and other elevated base metals. Concentric hydrothermal alteration haloes and joint-controlled vein sulfide stockwork, typical of copper-gold porphyries, are not developed in deposits of the study area. Deposits described by the porphyry gold model of Hollister (1992) are deficient in copper and contain abundant arsenic, like the peraluminous granite-porphyry gold polymetallic deposits of the study area. However, deposits in the model of Hollister (1992) contain tungsten, molybdenum, bismuth, and tellurium, which are generally absent in the peraluminous granite-porphyry gold polymetallic deposits of the study area.

Spurr (1906), Bercaw et al. (1987), and Prudden and Jucevic (1988) have described auriferous mineralization in the Mineral Ridge and Divide districts of southwest Nevada that is similar to that of the peraluminous granite-porphyry-hosted gold polymetallic deposits of the Kuskokwim mineral belt. In southwest Nevada, peraluminous granite-alaskite-aplite dikes and sills that intrude Cambro-Ordovician limestone and quartzite contain gold-silver mineralization. In the Divide district, high correlation coefficients exist among gold, silver, mercury, arsenic, and antimony (Prudden and Jucevic, 1988). In the Mineral Ridge district, Spurr (1906, p. 122–123) described "bodies of auriferous quartz, which probably separated in gelatinous form from alaskite during the process of crystallization and are of the same age and nature as the intergranular quartz of granite and alaskite." He further stated that the gold is principally in the free state, although some is contained in sulfides and feldspar phenocrysts. At the Donlin Creek peraluminous granite-porphyry-hosted gold polymetallic deposit, gold is found intergrown with feldspar phenocrysts and disseminated with arsenates in both dikes and country rock. At the Stuyahok peraluminous granite-porphyry-hosted mineralization in the Marshall-Anvik district, primary igneous(?) muscovite is found as radiating sunbursts in gold bullion derived from mineralized granite-porphyry.

Sidorov and Eremin (1995) and Nokleberg et al. (1993) have described mineralization in northeast Russia that is similar to the peraluminous granite-porphyry deposits of the study area. The Maiskoye deposit consists of stibnite, arsenopyrite, arsenic-rich pyrite, and uncommon lead and silver sulfosalts that occur in, and adjacent to, a large, north-south-trending dike and sill swarm of quartz feldspar porphyry, granite, granosyenite, porphyry, and lamprophyre that intrude Triassic siltstone. Linear alteration zones of sericitization and silicification envelop the dike and sill swarm. Up to 250 t of gold resources are contained in gold deposits at Maiskoye (Goryachev, 1995).

Regardless of specific deposit correlation, peraluminous granite-porphyry-hosted gold polymetallic deposits of the Kuskokwim mineral belt may belong to a new subclass of granitoid-related gold deposits.

Paradoxically, there is an inverse relationship between historical placer gold production and the current lode gold reserve bases associated with the two most important gold-bearing mineral deposit types. For example, 63 percent of past placer gold production in the study area is derived from plutonic-hosted copper-gold polymetallic deposits, but only 16 percent of the known lode reserves are associated with this deposit type. Conversely, 20 percent of past placer gold production and 84 percent of known lode gold resources of the study area are associated with peraluminous granite-porphyry-hosted gold polymetallic deposits. This inverse relationship of placer gold production to lode gold resource is probably caused mainly by geomorphological factors in three key areas. Plutonic-hosted copper-gold polymetallic deposits in the Iditarod-Flat district, which produced over half of the placer gold of the study area, have been dissected by mature third- and fourth-order streams that concentrated rich and productive placer gold deposits. Conversely, the Donlin district and Vinasale Mountain, which together contain about 84 percent of the study area's peraluminous granite-porphyry-associated lode gold resources, have been only weakly dissected by first- and second-order streams. In particular, Vinasale Mountain has been dissected by perennial streams that have almost no catchment basin development. Hence, the Donlin district and Vinasale Mountain have been subjected to significantly less mature heavy mineral placer development than the Flat district and have produced only modest amounts of placer gold.

Regional Implications

Almost all of the precious metal-bearing mineral deposits of the Kuskokwim mineral belt are related to the Late Cretaceous-early Tertiary igneous activity spanning the range of 77 to 52 Ma. Wallace and Engebretson (1984) suggested that the magmatic episode accompanied a period of rapid, northerly motion of the now-defunct Kula plate. Magmatic rocks of middle Tertiary age (50–35 Ma) are uncommon in the belt; workers including Moll-Stalcup (1994) and Wallace and Engebretson (1984) suggested this coincided with a period of plate reorganization prior to middle Tertiary to present-day subduction of the Pacific plate and formation of the Aleutian magmatic arc. Bradley et al. (1993) discussed the timing of early Tertiary ridge subduction in southern Alaska, citing isotopic ages from over 158 plutons in the area. According to their model, igneous rocks of the same age range as part of the Kuskokwim mineral belt (66–63 Ma) were formed above a slab window related to ridge subduction. Nokleberg et al. (1995) believe that the Late Cretaceous-early Tertiary magmatic arc(s) and associated metallogeny of interior and western Alaska developed during continued counterclockwise rotation of mainland Alaska and initiation of strike-slip faulting. These faults displaced previously accreted terranes and served as structural conduits for plutonism and volcanism. Moll and Patton (1982), Bergman and Doherty (1986), and Moll-Stalcup (1994) regarded the Late Cretaceous-early Tertiary igneous rocks of the Alaska Range and Kuskokwim Mountains as part of the same belt. Moll-Stalcup and Arth (1991) referred to both igneous belts as the Alaska Late Cretaceous-early Tertiary province, citing trace element, major oxide, and isotopic age data.

Hence, the origins of the Kuskokwim mineral belt are still being debated, although most workers agree that the magmatic rocks are subduction related. The results of this study agree with the suggestions of Bundtzen and Gilbert (1983), Gemuts et al., (1983), and Swanson et al. (1987) that the magmatism occurred in an intracontinental back-arc setting or in the landward portion of the Alaska Range magmatic arc, as indicated by (1) the alkali-calcic nature of the igneous rocks (more alkaline than many age-equivalent Alaska Range igneous suites), (2) wrench-fault tectonics in the study area, (3) the existence of peraluminous magmas, and (4) the types of mineral deposits in the belt. For example, deposits similar to the plutonic-hosted copper-gold polymetallic deposits and plutonic-related, boron-enriched silver-tin polymetallic deposits of the Kuskokwim mineral belt also occur in back-arc extensional environments in South America (Hollister, 1978). Sinclair (1986) suggested that early Tertiary peraluminous intrusions in Yukon Territory formed during extensional tectonism related to strike-slip faulting, which is what we advocate for emplacement of similar plutons, that is, the gold-bearing peraluminous granite-porphyry of the Kuskokwim mineral belt (Miller and Bundtzen, 1994).

Szumigala (1993) discussed the lack of a spatial pattern of incompatible element data from plutonic data in the Kuskokwim Mountains. In addition, isotopic age data (summarized by Solie et al., 1991) indicate a general absence of plutonic crystallization ages for the age range 70 to 60 Ma in the western Alaska Range; this same time span constitutes the most common mineral crystallization ages from plutons and volcanic rocks in the Kuskokwim Mountains.

Table 9 briefly compares the salient features of arc-related mineral belts in the Western Hemisphere that are similar to the Kuskokwim mineral belt. The mineral deposits of the study area compare to metallogenic belts associated with the early Tertiary Rocky Mountain alkalic province of central-eastern Montana (Wilson and Kyser, 1988; Mutschler et al., 1985, 1991), the Jurassic Mount Milligan alkalic complex of western Canada (Rebgliati, 1989), the late Tertiary plutonic and volcanic rocks of the Andean orogen of South America (Hollister, 1978), and the Okhotsk-Chukotka volcanogenic belt of the Russian northeast (Bely, 1994). The Andean orogen-Kuskokwim mineral belt comparison is restricted only to the Cenozoic elements of the Andean orogen, since differing styles of mineralization span the entire Mesozoic and Cenozoic in the former area.

The precious metal-bearing deposits of Late Cretaceous-early Tertiary age in the Okhotsk-Chukotka igneous belt in the Russian Far East can be compared with the Kuskokwim

TABLE 9. Generalized Comparison Between Subduction-Related Precious Metal Deposits in the Kuskokwim Mineral Belt and Selected Examples Worldwide

Mineral belt characteristics	Mount Milligan district, B.C. (Rebagliati, 1989)	Kuskokwim mineral belt (this study)	Rocky Mountains alkalic province (Mutschler et al., 1985; Wilson and Kyser, 1988)	Andean orogen; Cenozoic elements only (Hollister, 1978)	Okhotsk-Chukotka igneous belt; latest elements, Russian Far East (Bely, 1994)
General geology	Andesite-latite flow complexes intruded by porphyritic stocks of alkalic monzonite and syenite compositions	Volcanic-plutonic complexes, granite-porphyry dike and sill swarms, and subaerial volcanic fields; calcic intrusive compositions range from calc-alkaline to alkali-calcic; meta-aluminous to peraluminous varieties predominate	Andesite and latite volcanic piles intruded by alkalic stocks ranging in composition from monzodiorite to syenite	Andesitic volcanic piles intruded by mineralized plutons	Extensive Cretaceous-early Tertiary volcanic belt intruded by small plutons
Plutonic-mineral ages	Jurassic	55–77 Ma (Late Cretaceous and early Tertiary)	43–52 Ma (early to middle Tertiary)	4–65 Ma (Tertiary)	55–85 Ma (Late Cretaceous and early Tertiary)
Deposit types	(1) Alkalic Cu-Au stockwork; (2) epithermal Sb vein; (3) polymetallic skarn and replacement	(1) Plutonic-hosted Cu-Au polymetallic stockwork and vein; (2) peraluminous granite-porphyry-hosted Au-polymetallic; (3) plutonic-related, boron-enriched Ag-Sn-polymetallic; (4) gold-silver epithermal	(1) Polymetallic gold stockworks-porphyry; (2) epithermal Au-Ag; (3) replacement Pb-Zn	(1) Cu-Mo-Au porphyry stockworks; (2) tourmaline breccia pipes; (3) epithermal Au-Ag systems; (4) polymetallic vein-replacement	(1) Epithermal Au-Ag systems; (2) base metal porphyry systems; (3) plutonic-hosted Cu-Au stockwork; (4) Ag-Sn-polymetallic
Tectonic environment	Thought to be related to Jurassic subduction along western cordilleran margin	Back-arc, subduction-related igneous processes	Subduction, back arc, or intracontinental magmatic arc in an extensional environment	Subduction related; deposits more interior; volcanics more seaward	Subduction-related igneous processes

mineral belt, utilizing data from Bely (1994), Nokleberg et al. (1993), and Layer et al. (1994). Higher level, volcanic-hosted epithermal systems predominate in the former area, whereas plutonic-hosted precious metal-bearing systems seem to predominate in the Kuskokwim mineral belt. Otherwise, the similarities in trace element, isotopic age, structural, and tectonic frameworks are compelling for both areas.

Guidelines for Exploration

Miners panning placer gold and other heavy metallic minerals in stream, colluvial, and hill slope deposits of known placer camps have found many significant precious metal lode deposits in the Kuskokwim mineral belt. This time-proven technique continues to be a valuable exploration tool that delineates the boundaries of known gold-silver mineralization as well as discovery of new deposits in the Kuskokwim mineral belt. However, the absence of paying quantities of placer gold or specific heavy minerals in a given area does not necessarily imply that gold-silver resources are absent in that area. For example, placer gold resources are generally absent in glaciated highlands such as the Beaver, Horn, and Russian Mountains volcanic-plutonic complexes of the Kuskokwim mineral belt, even though gold-silver-bearing mineral deposits such as the Cirque, Tolstoi, Owhat-Mission Creek, and Whitewing exist in these uplands. Kline and Bundtzen (1986) attributed the absence of commercial gold placer deposits in the Beaver Mountains to dispersion and burial by glaciation. Glaciated highlands deserve diligent exploration work, because early prospectors relied almost exclusively on the gold pan as their principal exploration tool.

Discriminating plutonic rocks in the Kuskokwim mineral belt on the basis of chemistry (Newberry et al., 1988) and isotopic age should prove useful in determining mineral exploration targets. Nearly all the precious metal-bearing plutons in the study area are 70 to 65 Ma (Fig. 3). Most of the gold-silver-bearing plutons exhibit reduced character, based on their location on an alkalinity versus ferric/ferrous oxide ratio diagram (Leveille et al., 1988). For example, nearly all the larger monzonitic stocks associated with volcanic-plutonic complexes in the study area are gold favorable when subjected to this gold-discriminant method (Fig. 6). However, the granite-porphyry complexes, which contain 84 percent of the known gold reserves in the Kuskokwim mineral belt (Table 6), are gold unfavorable when plotted on the alkalinity versus ferric/ferrous oxide ratio diagram. Ubiquitous alteration in gold-bearing porphyry systems is thought by Leveille et al. (1988) to limit this gold-discriminant method. This may explain why the whole-rock igneous analyses from gold-bearing peraluminous granite-porphyry systems of the study area do not always plot in the gold-favorable field. Nevertheless, locating a pluton that both yields an age of 70 to 65 Ma and exhibits a reduced oxidation state might be a viable first step for a gold exploration program in the Kuskokwim mineral belt.

Soil geochemistry has been a successful exploration tool at the Chicken Mountain, Vinasale Mountain, Donlin Creek, Wattamuse Creek, and Candle Creek mineral deposits (Fig. 2). Because most of the Kuskokwim mineral belt has been subjected to mechanical erosion (as opposed to chemical erosion) in a periglacial, subarctic environment, gold and other heavy minerals liberated from hard-rock mineralization concentrate in soil cover. Specifically, the "C" soil horizon has proven capable of preserving detrital gold eroded from hard-rock mineralization at Candle Creek and Chicken Mountain (S. Dashevsky, pers. commun., 1988; R. Gosse, pers. commun., 1990).

Application of the metallogenic model presented in this paper can serve as a generalized exploration guide for precious metals in the Kuskokwim mineral belt. Plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein mineralization is usually localized in the cupola portions of volcanic-plutonic complexes. For example, precious metal mineralization appears to be confined to the highest 250 m of the intrusive rock on Chicken Mountain and in the Beaver Mountains; hence, focusing an exploration drilling effort on high-level plutons or in hornfels sedimentary or volcanic rocks that cap intrusions could lead to new discoveries. Furthermore, determining the extent of erosion of the cap rocks in volcanic-plutonic complexes and mineralized intrusions in known placer mining districts would assist in determining how much placer gold or other heavy minerals have been eroded from the mineral deposit and, more important, how much of the precious metal lode deposit(s) remains.

Published regional geophysical and radiometric surveys, which have been carried out by state and federal agencies, can help define target areas for precious metals in the Kuskokwim mineral belt. Reconnaissance gamma-ray spectrometer data were acquired by the National Uranium Resource Evaluation program in much of the study area (Aero Service Division, 1980a, b, c, d). Mineralized intrusive rocks such as the Beaver, Horn, and Russian Mountains show gamma-ray anomalies, which indicate that potassium-enriched igneous rocks exist in these areas.

Published 1:250,000-scale aeromagnetic surveys of the Sleetmute (Miller et al., 1989) and Medfra (Patton et al., 1982) quadrangles indicate that elliptical magnetic anomalies ranging from 300 to 700 γ indicate both exposed and buried plutons of mainly mafic and intermediate composition throughout the Kuskokwim mineral belt. Neither study could differentiate between reversed and normally magnetized plutons. In the time interval of the Late Cretaceous-early Tertiary metallogeny described in this paper (77–52 Ma), at least five magnetic field reversals are known (Ness et al., 1980). Mull et al. (1995) have interpreted similar magnetic anomalies underneath as much as 1,500 m of Quaternary and Tertiary sediments in the Bethel basin as being buried, reversed, and normally magnetized plutons of Late Cretaceous-early Tertiary age. Patton et al. (1982) discovered that several 200 to 500 γ anomalies corresponded to mineralized, thermally altered volcanic and sedimentary rocks in the Medfra quadrangle.

A regional aeromagnetic survey of the Iditarod quadrangle (Aero Service Division, 1982) revealed a large, 45-km^2 aeromagnetic low that overlies the Bismarck Creek hornfels aureole and associated tin-silver polymetallic prospect described in this paper; similar aeromagnetic lows probably indicate buried intrusions and might serve as guides to exploration for high-level precious metal mineral deposits.

DiMarchi (1993) used very low frequency surveys to define geochemical soil anomalies further and to refine structural controls in the Vinasale Mountain gold system.

Alteration might also guide exploration. DiMarchi (1993) described a propylitic halo surrounding the central ore zone at the Vinasale Mountain gold deposit. Szumigala (1993) mapped concentric silicate, quartz, and sulfide zones that envelop the Cirque, Tolstoi, and related deposits described in this paper in the west-central Beaver Mountains.

In summary, a variety of tools exist for mineral exploration in the Kuskokwim mineral belt. Much of the study area has undergone only reconnaissance-scale mineral resource investigations; we regard the region as a geologic frontier. In addition, approximately 85 percent of the land is owned by the state of Alaska and native corporations and is therefore open to mineral entry. Given these conditions, it is likely that significant gold-silver resources remain to be discovered in the Kuskokwim mineral belt.

Acknowledgments

Our mineral and geologic investigations in the Kuskokwim mineral belt began in the late 1970s and have continued to the present during 1:63,360-scale geologic mapping programs in the McGrath, Iditarod, Sleetmute, Russian Mission, Bethel, and Ophir quadrangles. Ten years ago, the Alaska Division of Geological and Geophysical Surveys and the U.S. Geological Survey cooperated in a resource study of the Iditarod 1:250,000 quadrangle; more recently they began joint studies in the Sleetmute quadrangle. Many of our colleagues who worked on these projects contributed to our understanding of the metallogeny of southwestern Alaska. G. Laird, B. Gamble, M. Lockwood, K. Bull, and J. Gray helped sample deposits and gather geologic data for mines and prospects throughout the study area. S. Swanson worked with K. Bull and T. Bundtzen on an earlier study of igneous rocks in the northern part of the study area. J. Bressler, J. Prey, E. Hodos, J. DiMarchi, R. Gosse, S. Dashevsky, P. Rush, J. Miscovich, D. Szumigala, R. Flanders, D. Cox, and L. Freeman, all of whom have studied mineral deposits in the Kuskokwim mineral belt, discussed various aspects of the regional geology and mineral deposits of the region and provided constructive comments. D. Szumigala made a significant contribution to the understanding of the northern part of the study area through his doctoral studies of the geology and mineralization in the Beaver Mountains and adjacent areas (Szumigala, 1993). K. Bull's (1988) work in the Flat district and J. DiMarchi's (1993) work on Vinasale Mountain likewise contributed to the understanding of precious metal-bearing Late Cretaceous-early Tertiary igneous complexes. We especially thank R. Retherford, J. McAtee, and the late B. Hickok of the Calista Corporation for sharing their knowledge of mineralized Late Cretaceous-early Tertiary igneous complexes in the southern portion of the study area. H. Noyes of Doyon Ltd. provided assistance for our work near Flat.

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