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PRECIOUS METALS ASSOCIATED WITH LATE CRETACEOUS-EARLY TERTIARY IGNEOUS ROCKS OF SOUTHWESTERN ALASKA

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

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Abstract

Precious metals associated with Late Cretaceous-Early Tertiary igneous rocks form an important metallogenic region in western and southwestern Alaska. These deposits lie within a belt that encompasses much of southwestern and part of western Alaska and is herein referred to as the Kuskokwim mineral belt. This belt has yielded 100,240 kg (3.22 Moz) of gold, 12,913 kg (412,000 oz) of silver, 1,377,412 kg (38,960 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 of the Kuskokwim mineral belt 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. This belt is named after the Kuskokwim Mountains, the principle geographic feature in the region. This paper 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 grace by rugged and locally glaciated, igneous-cored massifs. This study covers a region 550 km long by 350 km wide (192,500 km²) 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.
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 Inoko (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 Idoo Complex (Miller et al., 1991). The Late (?) Proterozoic to Paleozoic Ruby terrane (Patton et al., 1994) lies east and north of the Idoo 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
Jurassic clastic, carbonate, and volcanic rocks (Jones et al., 1982; Decker et al., 1994), which suggest that both basins filled in part by early Late Cretaceous time. The Yukon-Koyukuk basin deposits are largely volcanioclastic, 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, 1992). 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 postcre taceous 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 1. Gold, Silver, and Mercury Production from the Kuskokwim Mineral Belt of Southwestern Alaska, by Mining District, 1900-1995

<table>
<thead>
<tr>
<th>District</th>
<th>Total gold production (kg)</th>
<th>Placer gold (kg)</th>
<th>Lode gold (kg)</th>
<th>Silver (kg)</th>
<th>Mercury (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marshall-Anvik</td>
<td>3,835</td>
<td>3,835</td>
<td>NR</td>
<td>394</td>
<td>NR</td>
</tr>
<tr>
<td>Toksoi</td>
<td>3,450</td>
<td>3,450</td>
<td>NR</td>
<td>335</td>
<td>NR</td>
</tr>
<tr>
<td>Innoko</td>
<td>18,441</td>
<td>18,436</td>
<td>5</td>
<td>2,012</td>
<td>NR</td>
</tr>
<tr>
<td>McGrath-McKinley</td>
<td>6,117</td>
<td>4,074</td>
<td>2,043</td>
<td>770</td>
<td>1,723</td>
</tr>
<tr>
<td>Donlin</td>
<td>48,454</td>
<td>48,405</td>
<td>92</td>
<td>6,789</td>
<td>55</td>
</tr>
<tr>
<td>Anak-Tulukskak</td>
<td>16,803</td>
<td>16,803</td>
<td>NR</td>
<td>2,027</td>
<td>1,323,924</td>
</tr>
<tr>
<td>Bethel</td>
<td>1,336</td>
<td>1,336</td>
<td>NR</td>
<td>300</td>
<td>NR</td>
</tr>
<tr>
<td>Goodnews Bay</td>
<td>924</td>
<td>924</td>
<td>NR</td>
<td>120</td>
<td>NR</td>
</tr>
<tr>
<td>Total</td>
<td>100,240 kg</td>
<td>99,100 kg</td>
<td>2,146 kg</td>
<td>12,613 kg</td>
<td>1,377,412 kg</td>
</tr>
<tr>
<td></td>
<td>(3,223,000 oz)</td>
<td>(3,145,000 oz)</td>
<td>(68,810 oz)</td>
<td>(412,000 oz)</td>
<td>(39,960 flasks)</td>
</tr>
</tbody>
</table>

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

Includes production from the Flat, Moore, Julian, and Granite Creek camps.

Mercury production probably conservative; production from Kolmakof mine is unknown.

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.
## 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

<table>
<thead>
<tr>
<th>Deposit name</th>
<th>Deposit type</th>
<th>Principal commodities</th>
<th>Minerals found (t)</th>
<th>Gold (kg)</th>
<th>Silver (kg)</th>
<th>Copper (t)</th>
<th>Tin (kg)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken Mountains</td>
<td>Plutonic-hosted Cu-Au-polymetallic</td>
<td>Au, Ag, As, Sb, Cu</td>
<td>14,500,000</td>
<td>17,400</td>
<td>—</td>
<td>13,050</td>
<td>—</td>
<td>Bundtzen et al. (1992); V. Hollister, written commun. (1992)</td>
</tr>
<tr>
<td>Golden Horn</td>
<td>Plutonic-hosted Cu-Au-polymetallic</td>
<td>Au, As, W, Sb</td>
<td>2,550,000</td>
<td>3,420</td>
<td>9,650</td>
<td>—</td>
<td>—</td>
<td>Bundtzen et al. (1992)</td>
</tr>
<tr>
<td>Von Frank Mountain</td>
<td>Plutonic-hosted Cu-Au-polymetallic</td>
<td>Au, Cu</td>
<td>2,290,000</td>
<td>1,650</td>
<td>—</td>
<td>4,560</td>
<td>—</td>
<td>Bundtzen and Laird (1994)</td>
</tr>
<tr>
<td>Owshar-Minook Creek</td>
<td>Plutonic-hosted Cu-Au-polymetallic</td>
<td>Au, Ag, Cu</td>
<td>65,445</td>
<td>4,130</td>
<td>—</td>
<td>1,700</td>
<td>—</td>
<td>Bundtzen and Laird (1990); Hickey (1990b); this study</td>
</tr>
<tr>
<td>Native Fork</td>
<td>Plutonic-hosted Cu-Au-polymetallic, Au, Ag</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>Bundtzen et al. (1992)</td>
</tr>
<tr>
<td>Candle Hill</td>
<td>Plutonic-hosted Cu-Au-polymetallic</td>
<td>Au, Ag, Bi</td>
<td>85,445</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1985); Hickey (1990a); this study</td>
</tr>
<tr>
<td>Golden Horn</td>
<td>Plutonic-hosted Cu-Au-polymetallic</td>
<td>Au, Ag, Cu</td>
<td>40,270,000</td>
<td>114,560</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1985); Hickey (1990a); this study</td>
</tr>
<tr>
<td>Independence mine</td>
<td>Granite-porphyry Au-polymetallic</td>
<td>Au, Ag</td>
<td>20,000,000</td>
<td>3,540</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1982)</td>
</tr>
<tr>
<td>Vinsatee Mountains</td>
<td>Granite-porphyry Au-polymetallic</td>
<td>Au, Ag</td>
<td>10,000,000</td>
<td>24,840</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen et al. (1982); Bundtzen et al. (1995)</td>
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<tr>
<td>Granite and Julian</td>
<td>Granite-porphyry Au-polymetallic</td>
<td>Au, Ag</td>
<td>17,500,000</td>
<td>3,670</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1983, 1985a); Bundtzen et al. (1996); Nokleberg et al. (1993); this study</td>
</tr>
<tr>
<td>Creek</td>
<td>Granite-porphyry Au-polymetallic</td>
<td>Au, Ag</td>
<td>60,390</td>
<td>11,540</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1980); Nokleberg et al. (1992); Burleigh (1992a)</td>
</tr>
<tr>
<td>Cirque</td>
<td>Granite-related, boron-enriched</td>
<td>Cu, Ag, Sn</td>
<td>175,000</td>
<td>177,875</td>
<td>6,150</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1983); M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun. (1995)</td>
</tr>
<tr>
<td>Tokto</td>
<td>Granite-related, boron-enriched</td>
<td>Cu, Ag</td>
<td>1,500,000</td>
<td>1,500,000</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Bundtzen and Laird (1982); M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun. (1995)</td>
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<tr>
<td>Bismark Creek</td>
<td>Granite-related, boron-enriched</td>
<td>Ag, Sn, Cu, Zn</td>
<td>469,500</td>
<td>27,804</td>
<td>577</td>
<td>632,260</td>
<td>—</td>
<td>This study</td>
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<tr>
<td>Granite Mountain</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>5,000,000</td>
<td>5,000,000</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Win</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>5,000,000</td>
<td>5,000,000</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Won</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>1,937,000</td>
<td>1,937,000</td>
<td>1,531</td>
<td>11,476,000</td>
<td>—</td>
<td>Burleigh (1992a)</td>
</tr>
<tr>
<td>Pupinski</td>
<td>Plutonic-related, boron-enriched</td>
<td>Cu, Ag, Sn, Zn</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Ditina River</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>37,000</td>
<td>37,000</td>
<td>92</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Ekladof</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>37,000</td>
<td>37,000</td>
<td>92</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Pisgah Creek</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>37,000</td>
<td>37,000</td>
<td>92</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Yetna volcanic field</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>37,000</td>
<td>37,000</td>
<td>92</td>
<td>—</td>
<td>—</td>
<td>This study</td>
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<tr>
<td>Bogo Creek</td>
<td>Plutonic-related, boron-enriched</td>
<td>Ag, Sn</td>
<td>37,000</td>
<td>37,000</td>
<td>92</td>
<td>—</td>
<td>—</td>
<td>This study</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>77,482,005</td>
<td>162,572</td>
<td>201,015</td>
<td>28,088</td>
<td>12,158,340</td>
<td>This study</td>
</tr>
</tbody>
</table>

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.

*PRECIOUS METALS ASSOCIATED WITH IGNEOUS ROCKS, SW AK*
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).
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. 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 KAr/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.

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, Chulihnik, and Klookluk 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 Kuskup 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-km² Beaver Mountains complex (the largest) to the 8-km² 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 Chulihnik and Klookluk 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., 1985). 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. 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 Ar/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; 43 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 isotopic 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 precreational terranes in the Yetna River drainage (Iditarod and Holy Cross quadrangles), in the Blackburn Hills area (Unalakleet and Holy Cross quadrangles), and along the northern flanks of the Kilbuck Mountains (Bethel and Russian Mission quadrangles). These volcanic fields range from 50 km² at Wolf Creek Mountain to about 5,000 km² in the Yetna River area, which makes them the most aerially extensive of the Late Cretaceous-early Tertiary igneous rocks in the study area (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 granite-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 40Ar/39Ar 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 km². 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.

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 Fe₂O₃/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.
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 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 Lierl (1983b), Bundtzen et al. (1992), Bundtzen et al. (1993), Miller and Bundtzen (1994), and authors (unpub. data).

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 Lierl (1983b), Bundtzen et al. (1992), Bundtzen et al. (1993), Miller and Bundtzen (1994), and authors (unpub. data).

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

<table>
<thead>
<tr>
<th>Field no.</th>
<th>Rocky type</th>
<th>Locality</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>$^{87}$Rb/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr (initial)</th>
<th>$^{87}$Sr/$^{86}$Sr (initial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78BT435</td>
<td>Monzonite</td>
<td>Mount Joaquin</td>
<td>115</td>
<td>550</td>
<td>0.574</td>
<td>0.70555</td>
<td>0.70490</td>
</tr>
<tr>
<td>78BT461</td>
<td>Monzodiorite</td>
<td>Takoma</td>
<td>141</td>
<td>475</td>
<td>0.656</td>
<td>0.70611</td>
<td>0.70526</td>
</tr>
<tr>
<td>78BT370</td>
<td>Monzonite</td>
<td>Candle Hills</td>
<td>138</td>
<td>541</td>
<td>0.736</td>
<td>0.70653</td>
<td>0.70685</td>
</tr>
<tr>
<td>82BT431</td>
<td>Alkali gabbro</td>
<td>Golden Horn-Black Creek</td>
<td>155</td>
<td>619</td>
<td>0.725</td>
<td>0.70544</td>
<td>0.70472</td>
</tr>
<tr>
<td>81BT524</td>
<td>Basalt</td>
<td>Beaver Mountains</td>
<td>236</td>
<td>631</td>
<td>1.092</td>
<td>0.70613</td>
<td>0.70505</td>
</tr>
<tr>
<td>77BT234</td>
<td>Basalt</td>
<td>Candle Hills</td>
<td>106</td>
<td>518</td>
<td>0.591</td>
<td>0.70712</td>
<td>0.70653</td>
</tr>
</tbody>
</table>

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 $-1.42 \times 10^{-10}$ yr$^{-1}$ and age = 70 Ma
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 argil- lic 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 deposi tional 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 H2O (Bundtzen et al., 1995; 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 alkaline porphyry copper-gold model of Lowell and Gulbert (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

<table>
<thead>
<tr>
<th>Au</th>
<th>Ag</th>
<th>As</th>
<th>Sb</th>
<th>Hg</th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
<th>Bi</th>
<th>Cr</th>
<th>U</th>
<th>Th</th>
<th>Mo</th>
<th>Nb</th>
<th>Sn</th>
<th>No of samples analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of</td>
<td>samples</td>
<td>References</td>
<td></td>
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<tr>
<td>Plutonic-hosted copper-gold-polymetallic deposits</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chicken Mountain</td>
<td>1.20</td>
<td>4.6</td>
<td>617</td>
<td>53</td>
<td>1.56</td>
<td>490</td>
<td>17</td>
<td>46</td>
<td>1.0</td>
<td>165</td>
<td>4.3</td>
<td>8.0</td>
<td>65</td>
<td>31.0</td>
<td>7</td>
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<tr>
<td>Golden Horn</td>
<td>9.90</td>
<td>21.5</td>
<td>19,000</td>
<td>12,000</td>
<td>2.96</td>
<td>243</td>
<td>210</td>
<td>75</td>
<td>5.0</td>
<td>204</td>
<td>3.0</td>
<td>8.5</td>
<td>3</td>
<td>21.0</td>
<td>22</td>
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<tr>
<td>Russian Mountain</td>
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<td>85,600</td>
<td>2,000</td>
<td>ND</td>
<td>5,700</td>
<td>1,042</td>
<td>287</td>
<td>93.0</td>
<td>281</td>
<td>12.4</td>
<td>9.1</td>
<td>1.8</td>
<td>23.0</td>
<td>22</td>
</tr>
<tr>
<td>Lodes</td>
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<td>ND</td>
<td>ND</td>
<td>290</td>
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<td>20</td>
<td>8.8</td>
<td>23.3</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
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<tr>
<td>Noon Fork-Mystery</td>
<td>16.70</td>
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<td>653</td>
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<td>1,763</td>
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<td>Peramoxous granite-porphyry-hosted gold-polymetallic deposits</td>
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<tr>
<td>Donlin</td>
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<td>Ganes-Yankee Creek</td>
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<td>ND</td>
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<td>1,645</td>
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<td>54</td>
<td>5</td>
<td>ND</td>
<td>129</td>
<td>5.1</td>
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<td>ND</td>
<td>ND</td>
<td>ND</td>
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<td>5</td>
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<tr>
<td>Granite Creek</td>
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<td>54,305</td>
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<td>12</td>
<td>11</td>
<td>50</td>
<td>ND</td>
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<td>ND</td>
<td>ND</td>
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<td>Plutonic-related, boron-enriched silver-tin-polymetallic deposits</td>
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<tr>
<td>Cirque</td>
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<td>718</td>
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<td>41,369</td>
<td>9,123</td>
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<td>183</td>
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<td>373.6</td>
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<tr>
<td>Kolinakof</td>
<td>1.02</td>
<td>3.6</td>
<td>17</td>
<td>250</td>
<td>&gt;50.0</td>
<td>35</td>
<td>15</td>
<td>46</td>
<td>0.5</td>
<td>312</td>
<td>1.5</td>
<td>4.0</td>
<td>ND</td>
<td>ND</td>
<td>85</td>
</tr>
<tr>
<td>Glenn Creek</td>
<td>2.08</td>
<td>135.9</td>
<td>1,266</td>
<td>7,147</td>
<td>2.02</td>
<td>342</td>
<td>175</td>
<td>74</td>
<td>6.1</td>
<td>250</td>
<td>ND</td>
<td>7.8</td>
<td>ND</td>
<td>ND</td>
<td>5</td>
</tr>
<tr>
<td>Dahlen River</td>
<td>1.02</td>
<td>0.1</td>
<td>3,762</td>
<td>4,868</td>
<td>4.10</td>
<td>15</td>
<td>35</td>
<td>19</td>
<td>ND</td>
<td>32</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Bogus Creek</td>
<td>0.59</td>
<td>107.3</td>
<td>57</td>
<td>38</td>
<td>2.19</td>
<td>70</td>
<td>172</td>
<td>67</td>
<td>ND</td>
<td>17</td>
<td>ND</td>
<td>ND</td>
<td>9.0</td>
<td>ND</td>
<td>10</td>
</tr>
</tbody>
</table>

Data derived from references 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.
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 ± 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 54 kg (2.706 oz) of gold and 81 kg (2.680 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 wehlrite 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 (oxygenite, acanthite), 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 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 chrome-tile, (3) extensive chlorite alteration; dolomite breccia veins introduced synchronously with open-space sulfide deposition (Figs. 7A, 8B, C), (4) lead-antimony-scheelite-gold-owyheeite stockwork-type, platinum group mineralization is hosted in quartz diorite and augite-rich biotite granodiorite (Fig. 9). The work in monzonite-porphyry (Fig. 7B), (3) arsenopyrite-bro, (2) extensive sericite-ankerite-quartz and minor chrome-tile, en echelon veinlets cutting monzodiorite, and alkali gabbro, (2) extensive sericite-ankerite-quartz and minor chrome-tile alteration, mainly as veinlets or replacements in breccias and minor chalcopyrite-molybdenite-quartz stockwork accompanied by extensive chlorite alteration; dolomite breccia veins introduced synchronously with open-space sulfide deposition (Figs. 7A, 8B, C), (4) lead-antimony sulfosalts-gold-oxyheite-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-induced 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 chalcocyanite, 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 et al., 1992).
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 deposit.
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 and Laird, 1983b). An ankerite alteration zone ranging from 5 to 15 m wide can be traced for about 350 m along the Golden Horn Chloritic and dolomitic (event 2) alteration; local fluorite introduction control, 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 \((\text{Cu(UO}_2\text{)}_2 \cdot (\text{AsO}_4\text{)}_2 \cdot 8\text{H}_2\text{O})\), 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, 

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 \((\text{Cu(UO}_2\text{)}_2 \cdot (\text{AsO}_4\text{)}_2 \cdot 8\text{H}_2\text{O})\), 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,
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 (1978), 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 exist 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 diorite to quartz monzonite 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 0.5 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 sericite 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 Teltsina Formation, which forms the base of the Nixon Fork terrane about 50 km northeast of McGrath (Fig. 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 Herreed (1986), 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 metallic content, alteration style, and spatial distribution of placer gold deposits surrounding the mineralized plutons in the study area may have formed in high-level, lower mesothermal to epithermal conditions.

Active dike swarms contain more than one intrusive event.
Porphyritic andesite flows and tuff
Undifferentiated metamorphic and metavolcanic rocks of Goodnews Terrane and Quaternary cover

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

Explanation

- TKgd: Granodiorite to quartz monzonite; K-Ar = 71.3 Ma
- TKv: Porphyritic andesite flows and tuff
- Undifferentiated metamorphic and metavolcanic rocks of Goodnews Terrane and Quaternary cover
- Zone of thin stockwork veins with sericite, quartz, and chalcopyrite
- Placer deposit
- - High angle fault

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 prob-
Precious Metals Associated with Igneous Rocks, SW AK

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 distinctly 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 shear 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 (3.6 million oz) gold (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 southeast towards the high-angle Beaver Mountain 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 the ore mineralization.
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-carbon-
ate 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 molybde-
num, arsenic, copper, lead, and silver. The Arnold and re-
lated 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-km² pluton consisting of monzonite, quartz monzonite, and granite-porphyry intruded the Kuskokwim Group at Vinasse Mountain, about 25 km south of McGrath. Recent industry exploration efforts summarized by DiMarchi (1993) have delineated one of the most
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 gullie 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...
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
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 Slelat, 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-km² 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-
manganese-axinite stockwork covers an elliptically shaped zone 200 m² in hornefels sandstone above syenite intrusive rocks of the Tatalina Mountain pluton about 35 km west-southwest of McGrath (Figs. 2, 7). 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 km² 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, 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 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 percent 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. 71). A 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-tin 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, pervasive, 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 75 Ma from hydrothermally altered mafic basalt at the DeCourcy Mountain mercury-antimony mine (Fig. 2). Gray et al. (1992) reported a Ar39/Ar40 plateau age of 72.5 Ma from hydrothermal sericite at the Fairview mercury-antimony deposit near Sleetmute and a Ar39/Ar40 minimum age of 72 Ma from hydrothermal sericite at the Rhyolite mercury prospect on Juninggula 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-Tululok 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 (1983, 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 160° to 210°C (Miller et al., 1989). Assuming CO2 densities of 0.25 g/cm3 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 H₂O and up to 4 percent CO₂ and contain trace amounts of N₂ and CH₄ (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). Chalcodonic-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-
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
fossils discovered by the late Bruce Hickok from chalcedonic breccia at Bogus Creek resemble the Late Cretaceous forms—either Cladophlebis septentrionalis or Nilsoni 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-Tuluksk, 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 1985 (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 fine- 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 sources 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 the peraluminous granite-porphyry-hosted gold polymetallic systems (Table 6).

Gold-bearing placer deposits formed downslope or down-stream 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-Tuluksk district have fineness values ranging from 838 to 914 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 g of gold 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 relic 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

<table>
<thead>
<tr>
<th>Deposit type</th>
<th>Geology of host rocks</th>
<th>Plutonic-volcanic compositions</th>
<th>Mineralogy of ore</th>
<th>Structure, morphology</th>
<th>Alteration</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plutonic-hosted copper-gold-polymetallic stockwork-vein (skarn)</td>
<td>Volcanic-plutonic complexes intrusive Kuskokwim Group and Nuklik terrane; some plutonic intrusive Paleozoic limestones</td>
<td>Heterogeneous and variable, from alkali gabbro to granite; many average magnetite, generally meta-aluminous and range from 40 to 67% SiO₂, contains elevated Th and U, generally reduced (ferromanganese ratio) conditions</td>
<td>Deeper levels contain chalcopyrite, molybdenite, scheelite, and arsenopyrite; upper levels contain Ag-Sb sulfosalts, arsenides, stibnite, free gold; chilled shams contain cupriferous and malachitic protore rich in bornite and chalcopyrite</td>
<td>Vertically zoned systems in intrusive stockworks, minor stockworks 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 hornfels near plutons, best target for skarn deposits</td>
<td>Ankerite, potassic, propylitic (sulfosalt-zonation), and silicic alteration, no clear patterns developed in most mineralized plutons; early pyroxene magnetite-garnet, later wollastonite in skarn types</td>
<td>Accounts for 25,980 kg gold, or 16% of known lode gold resources in the Kuskokwim mineral belt</td>
</tr>
<tr>
<td>2. Peraluminous granite-porphyry dikes and sills that give way to shallow intrusions</td>
<td>Several varieties of peraluminous alkali to alkaline granite, frequently containing garnet, heavyREE, depletion trends, possible product of crustal melting, both oxidized and reduced intrusive processes</td>
<td>Silicate, clinvar, arsenopyrite, Sb sulfosalts</td>
<td>Generally high-level replacement along high-angle faults (Ganes-Yankee and Donlin faults): orebodies are distinct lenses in both porphyry and host rocks</td>
<td>Agzinc, potassic, and silicic alteration plus dickite</td>
<td>Accounts for 136,500 kg gold, or 54% of known lode gold resources in the Kuskokwim mineral belt</td>
<td></td>
</tr>
<tr>
<td>3. Plutonic-related hosted in hornfels sedimentary rock, volcanic rocks, and peraluminous-golden basic rocks; chalcopyrite, salma; abundant replacements metasomatism; silicic deposit type; potentially silver-tin usually a component of volcanic-plutonic complexes, which intrude Kuskokwim Group flysch</td>
<td>Meta-aluminous to peraluminous; underutilized, reduced, phonolitic rocks, the younger ages predominating, fewer intrusive phases than type 1 above</td>
<td>Cassiterite, Ag-Sb sulfosalts, chalcopyrite, molybdenite, abundant tourmaline, quartz, and tourmaline gneissic minerals</td>
<td>Veins, stockwork, and replacements</td>
<td>Strong base metamorphism; silicic alteration in intrusion-related types; saddle-tourmaline veins and stockwork in hornfels</td>
<td>Recently recognized deposit type; potentially large silver resources may be found part of deposit type 1 above</td>
<td></td>
</tr>
<tr>
<td>4. Epithermal gold-silver systems</td>
<td>Highly variable: (1) associated with altered magmatic dikes; (2) disseminated in stockwork deposit types above; (3) chalcedonic veins and stockwork zones in host rocks; (4) High altered olivine boudins; (5) meta-aluminous, reduced, metasomatized to granite porphyry; (6) calc-alkaline andesite to rhyolite, volcanic host rocks</td>
<td>(1) Clinvar, stibnite, free gold; (2) clinvar, stibnite, arsenides, Ag sulfosalts; (3) na; (4) clinvar</td>
<td>High-level systems in all cases: (1) introduction along faults; (2) as disseminated in porphyry or vein type Ag Au-polymetallic deposits; (3) as ring structures distal to volcanic calderas; (4) Silica-carbonate and dickite; (5) potassic, phyllite; (6) calc-alkaline, adularia</td>
<td>(1) Silica-carbonate and dickite; (2) potassic, phyllite; (3) calc-alkaline, adularia</td>
<td>poorest understood of all gold-silver resources of study area, accounts for &lt;1% of known gold resources in Kuskokwim mineral belt</td>
<td></td>
</tr>
</tbody>
</table>
| 5. Heavy mineral placer deposits | Stream, colluvial, and residial accumulations derived from erosion of mineral deposits listed above | Free gold, electrum, cinnabar, stibnite, ilmenite, magnetite-chromite, cassiterite, monazite, garnet, edenite, richterite, scheelite, radioactive zircon, ilmenorutile, trace platinum-group elements | NA | Lode sources for 96,310 kg placer gold mined in Kuskokwim mineral belt (1990-1995) derived as follows: plutonic-hosted Cu-Au stockwork and vein, 51,486 kg (63%); peraluminous granite-porphyry Au-polymetallic, 20,191 kg (22%); middle Cretaceous plutons, 13,697 kg (14%); all other types, 2,722 kg (3%)

NA = not available
<table>
<thead>
<tr>
<th>District</th>
<th>Geology of presumed lode source</th>
<th>Gold fineness</th>
<th>Major and minor heavy minerals</th>
<th>Anomalies, remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolstoi</td>
<td>Late Cretaceous-early Tertiary, meta-aluminous, alkali-calcic to quartz alkalic plutons of monzonitic composition</td>
<td>864–902; avg = 897</td>
<td>Zircon, magnetite, ilmenite, samarskite, powellite, xanthoconite, cassiterite</td>
<td>Platinum in gold bullion at Colorado Creek; anomalous tin, niobium, molybdenum, and uranium; silver sulfides</td>
</tr>
<tr>
<td>Innoko</td>
<td>Bimodal dike swarm; 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</td>
<td>846–898; avg = 853</td>
<td>Magnetite, cinnabar, chromite or magnesio-chromite, scheelite, monazite, ilmenorutile, native silver, platinum</td>
<td>Sphalerite very abundant in Little Creek; platinum from Boo Creek probably derived from Jurassic ophiolite</td>
</tr>
<tr>
<td>McKinley-McGrath</td>
<td>Meta-aluminous, quartz alkalic monzonitic plutons in Candle Hills; all of Late Cretaceous-early Tertiary age</td>
<td>894–902; avg = 908</td>
<td>Magnetite, magnesio-chromite, cinnabar, ilmenite, monazite, sodic amphibole, scheelite, platinum</td>
<td>Anomalous platinum in gold bullion; niobium end member in ilmenorutile</td>
</tr>
<tr>
<td>Iditarod (Moore)</td>
<td>Meta-aluminous, alkali-calcic boron-enriched plutons of monzonitic composition; Late Cretaceous-early Tertiary age</td>
<td>759–833; avg = 833</td>
<td>Chromite, cinnabar, native silver, silver sulfosalts</td>
<td>Highest silver/gold ratio of any district</td>
</tr>
<tr>
<td>Iditarod (George)</td>
<td>Both meta-aluminous, alkali calcic monzonite and peraluminous granite-porphyry (very similar to Innoko-Ophir); both suites of Late Cretaceous-early Tertiary age</td>
<td>835–857; avg = 833</td>
<td>Magnetite, garnet, cinnabar, stibnite, monazite</td>
<td>Julian Creek has most radioactive concentrates of all examined</td>
</tr>
<tr>
<td>Iditarod (Flat)</td>
<td>Meta-aluminous, quartz alkalic gabbros to monzonite plutons of Late Cretaceous-early Tertiary age</td>
<td>847–874; avg = 867</td>
<td>Cinnabar, chromite, arsenopyrite, pyrite, zircon, cinnabar, ilmenorutile, scheelite, cassiterite</td>
<td>Anomalous platinum in gold bullion; uranium in zircon; scheelite and cinnabar very abundant in Otter Creek drainage</td>
</tr>
<tr>
<td>Donlin</td>
<td>Peraluminous granite-porphyry dikes of Late Cretaceous-early Tertiary age</td>
<td>800–901; avg = 877</td>
<td>Garnet, cassiterite, stibnite, monazite, cinnabar</td>
<td>Radioactive concentrates similar to Julian Creek; mercury content in selected gold grains from Snow Creek ranges from 3.55 to 9.18%</td>
</tr>
<tr>
<td>Aniak-Taluluk</td>
<td>Mineralized middle Cretaceous pluton is probable source of about 70% of placer gold; remainder derived from Late Cretaceous-early Tertiary plutons and epithermal veins</td>
<td>835–994; avg = 933</td>
<td>Stibnite, cinnabar, magnesite, cassiterite, chalcopyrite</td>
<td>Gold from Bear Creek contains minor intergrowths of chalcopyrite; Spruce Creek gold contains gold telluride calaverite and inclusions of rutile in gold</td>
</tr>
<tr>
<td>Bethel</td>
<td>Veins in monzonite to granodiorite plutons of Late Cretaceous-early Tertiary age</td>
<td>avg = 873</td>
<td>Cinnabar, zinc, ilmenorutile</td>
<td>Gold from Eureka Creek contains aurostibite (AuSb) and bismuth sulfosalts</td>
</tr>
<tr>
<td>Marshall-Anvik</td>
<td>Peraluminous, granite-porphyry dikes, sill, and small plutons intrude Lower Cretaceous (Neocomian) volcanic and volcaniclastic rocks of Yukon-Koyukuk terrane</td>
<td>654–973; avg = 817</td>
<td>Cinnabar, stibnite, arsenopyrite, pyrite, monazite</td>
<td>Gold grains from Flat Creek show intricate vernacular sunburst muscovite inclusions</td>
</tr>
</tbody>
</table>

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 differ-
ent 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, 1980)
and is probably the result of greater solidification activity re-
sulting 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 mate-
rials 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 migra-
tion, the stream leaves a successive series of older alluvial
terraces. Many placer gold-bearing drainages in the Kuskok-
wim 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 show-
ing 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 asym-
metry 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 subeconomical) Donlin bench, an
ancestral drainage of Donlin Creek (Fig. 11). Donlin Creek
originally flowed northeast into the Iditarod River, which
eventually drained 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 de-
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 develop-
ment 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 Canes-Yankee Creek areas of the
Innoko district (Figs. 2, 12, 13), gold polymetallic placer de-
posits 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-por-
phyry dikes, sills, and stocks.

Placer gold has been found in small quantities in the Bea-
ver, Russian, and Horn Mountains, all of which contain gold-
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 contain 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
precious metals associated with igneous rocks, sw ak

1. Granitic porphyry gold-polymetallic deposit type
2. Gold-silver epithermal systems
3. Volcanic/plutonic complex with plutonic associated boron enriched silver/polymetallic systems
4. Volcanic/plutonic complex Plutonic-hosted gold-copper stockwork and vein deposits

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 alcaline 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 40Ar/39Ar 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...
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 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.

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polymetallic deposit type and a structurally controlled silver- and thorium, and low zinc values, which are characteristic of the Nixon Fork pluton hosts both skarns (the Nixon Fork tin-copper deposit, which is thought to be the boron-enriched silver-tin polymetallic type) and the plutonic-hosted copper-gold 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 deposit type, 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 study area is problematical. Copper is usually absent in 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 Jucovic (1988) have described auriferous mineralization in the Mineral Ridge district, high correlation coefficients exist among gold, silver, mercury, arsenic, and antimony (Prudden and Jucovic, 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, and 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 extrusive (nonpluton-related) and mixed origin (plutonic and metamorphic) deposits after Newberry et al. (1995).
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, granopyroxenite, 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 resource 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 tectonics 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 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 (Rebliati, 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
**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, Horon, 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 y 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 underneat both 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 y 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-km² 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. 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.

We especially thank W. Nokleberg for his helpful advice during our work in the Kuskokwim mineral belt. The senior author compiled descriptive data for polymetallic mineral deposits from southwestern Alaska for a comparative regional metallogenic study of Alaska and the Russian northeast, which was published in Nokleberg et al. (1993).
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