

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

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Abstract

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

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

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

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

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

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

Introduction

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

The Kuskokwim Mountains form a broad northeast-trend-

ing belt of accordant rounded ridges and broad sediment-filled lowlands occasionally graced by rugged and locally glaciated, igneous-cored massifs. This study covers a region 550 km long by 350 km wide (192,500 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.

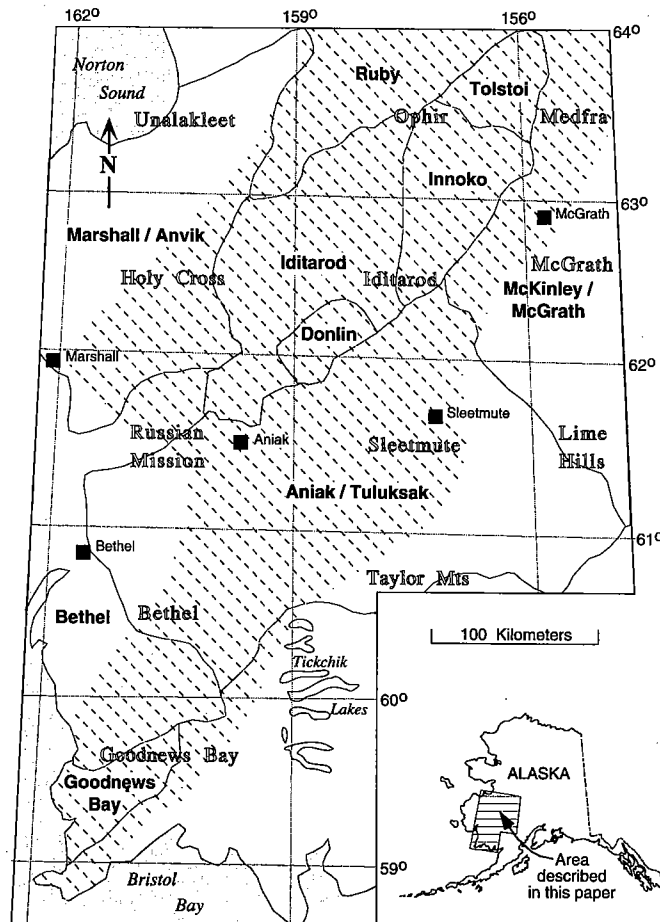


FIG. 1. Map of the Kuskokwim mineral belt (hatched pattern), showing principal settlements (solid squares), 1:250,000 quadrangles (outlined lettering), and boundaries of historic gold mining districts, as summarized by Ransome and Kerns (1954).

A brief history of mineral resource development

In the first half of the nineteenth century, Russians explored the southern Kuskokwim Mountains and in 1838 found cinnabar-stibnite deposits near Kolmakof Fort; this was the first mineral discovery made by Russians in Alaska (Spurr, 1900). The search for paying quantities of gold in the Kuskokwim mineral belt began with the Aniak discoveries of 1901. These were followed successively by the Innoko (1906), Iditarod (1909), Nixon Fork (1910), Marshall (1913), and Tolstoi (1916) discoveries. These placer gold rushes prompted a series of geologic and mineral resource investigations by the U.S. Geological Survey in the Kuskokwim River basin (Madden, 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 depos-

its—first, mesothermal polymetallic gold and epithermal mercury-antimony vein deposits and, later, strategic mineral deposits such as platinum at Goodnews Bay (see footnote in Table 1). Lode gold mining took place intermittently from 1911 to 1960. Mercury mining began in the 1920s, peaked in the 1950s, and had ceased by the mid-1970s.

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

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

Regional Geology and Tectonic Setting

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

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

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

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

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

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

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

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

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

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

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

Amalgamation of the lithotectonic terranes of western Alaska was completed prior to middle Cretaceous time (Decker et al., 1994; Patton et al., 1994). Subsequently, these older terranes were eroded and partly covered by terrigenous clastic rocks deposited into the Yukon-Koyukuk and Kuskokwim basins. Both basin fill sequences are middle to Late Cretaceous in age and have prograding turbidite, shallow-marine, and shoreline facies (Miller and Bundtzen, 1994; Patton et al., 1994), which suggest that both basins filled in

by early Late Cretaceous time. The Yukon-Koyukuk basin deposits are largely volcanoclastic, reflecting erosion of the surrounding Koyukuk and Angayucham-Tozitna terranes (Patton et al., 1994). The regionally extensive Upper Cretaceous Kuskokwim Group was deposited primarily by turbidity currents into an elongate, probably strike-slip basin (Bundtzen and Gilbert, 1983; Miller and Bundtzen, 1994). Local interbedded tuffs and volcanoclastic sandstone in the Kuskokwim Group indicate a provenance sometimes similar to the Yukon-Koyukuk basin deposits, but much of the Kuskokwim Group is derived from a mixture of sedimentary and metamorphic terranes (Decker et al., 1994).

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

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

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

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

Deposit name	Deposit type	Principal commodities	Mineralization (t)	Gold (kg)	Silver (kg)	Copper (t)	Tin (kg)	References
Chicken Mountain	Plutonic-hosted Cu-Au-polymetallic	Au, Ag, As, Sb, Cu	14,500,000	17,400	—	13,050	—	Bundtzen et al. (1992); V. Hollister, written commun. (1992)
Golden Horn	Plutonic-hosted Cu-Au-polymetallic	Au, As, W, Sb	2,850,000	3,420	9,690	—	—	Bundtzen et al. (1992)
Von Frank Mountain	Plutonic-hosted Cu-Au-polymetallic	Au, Cu	—	—	—	—	—	J. DiMarchi, pers. commun. (1993)
Owhat-Mission Creek	Plutonic-hosted Cu-Au-polymetallic	Au, Ag, Cu, As	229,000	1,030	—	4,589	—	Bundtzen and Laird (1991)
Wattamuse prospect	Plutonic-hosted Cu-Au-polymetallic	Au, Ag	—	—	—	—	—	Hickok (1990b); this study
Itkik prospect	Plutonic-hosted Cu-Au-polymetallic	Au, Ag	—	—	—	—	—	Hickok (1990a); this study
Nixon Fork	Au-Cu-Bi skarn associated with deposit type above	Au, Ag, Cu, Bi	85,345	4,130	—	1,706	—	Bundtzen et al. (1994)
Candle Hills	Plutonic-hosted Cu-Au-polymetallic	Au, Ag, Cu	—	—	—	—	—	Bundtzen and Laird (1983b); this study
Donlin	Granite-porphphy Au-polymetallic	Au, Ag, Sb	40,370,400	111,960	—	—	—	Retherford and McAtee (1994); Bundtzen et al. (1996); this study
Independence mine	Granite-porphphy Au-polymetallic	Au, Ag, Sb	—	—	—	—	—	Bundtzen and Laird (1983, 1983a); this study
Vinasale Mountain	Granite-porphphy Au-polymetallic	Au, Ag	10,300,000	24,540	—	—	—	DiMarchi (1993); Bundtzen (1986); Swainbank et al. (1995)
Granite and Julian Creeks	Granite-porphphy Au-polymetallic	Au, Ag, Sb	—	—	—	—	—	Bundtzen et al. (1985)
Ophir dike swarm	Granite-porphphy Au-polymetallic	Au, Ag	—	—	—	—	—	Bundtzen and Laird (1980); this study
Arnold-Willow Creek prospect	Granite-porphphy Au-polymetallic	Au, Ag	—	—	—	—	—	Nokleberg et al. (1993); this study
Cirque	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Cu, Ag, Sn	175,000	—	77,875	6,125	—	Bundtzen and Laird (1982); M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun. (1995)
Tolstoi	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Cu, Ag	1,500,000	—	—	—	—	Bundtzen and Laird (1982); M.L. Miller, T.K. Bundtzen, and J.E. Gray, written commun. (1995)
Bismarck Creek	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn, Cu, Zn	498,000	—	23,804	797	682,260	Bundtzen, and J.E. Gray, written commun. (1995)
Granite Mountain pipe	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn	5,000,000	—	—	—	—	This study
Win	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn	—	—	—	—	—	Burleigh (1992a)
Won	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Ag, Sn	1,937,060	—	89,646	1,821	11,476,080	Burleigh (1992b)
Pupinsa	Plutonic-related, boron-enriched Ag-Sn-polymetallic	Cu, Ag, Sn, Zn	—	—	—	—	—	This study
Dishna River	Au-Ag epithermal	Au, Ag, Sb	37,600	92	—	—	—	This study
Kolmakof	Au-Ag epithermal	Hg, Sb, Au, Ag, Te	—	—	—	—	—	Bundtzen et al. (1993); this study
Poison Creek	Au-Ag epithermal	Au, Ag, Hg	—	—	—	—	—	This study
Yetna volcanic field	Au-Ag epithermal	Ag, Au	—	—	—	—	—	This study
Bogus Creek	Au-Ag epithermal	Ag, Au, Sb	—	—	—	—	—	This study
Total	—	—	77,482,405	162,572 (5,227,000 oz)	201,015 (6,464,000 oz)	28,088	12,156,340 (12,160 t)	—

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

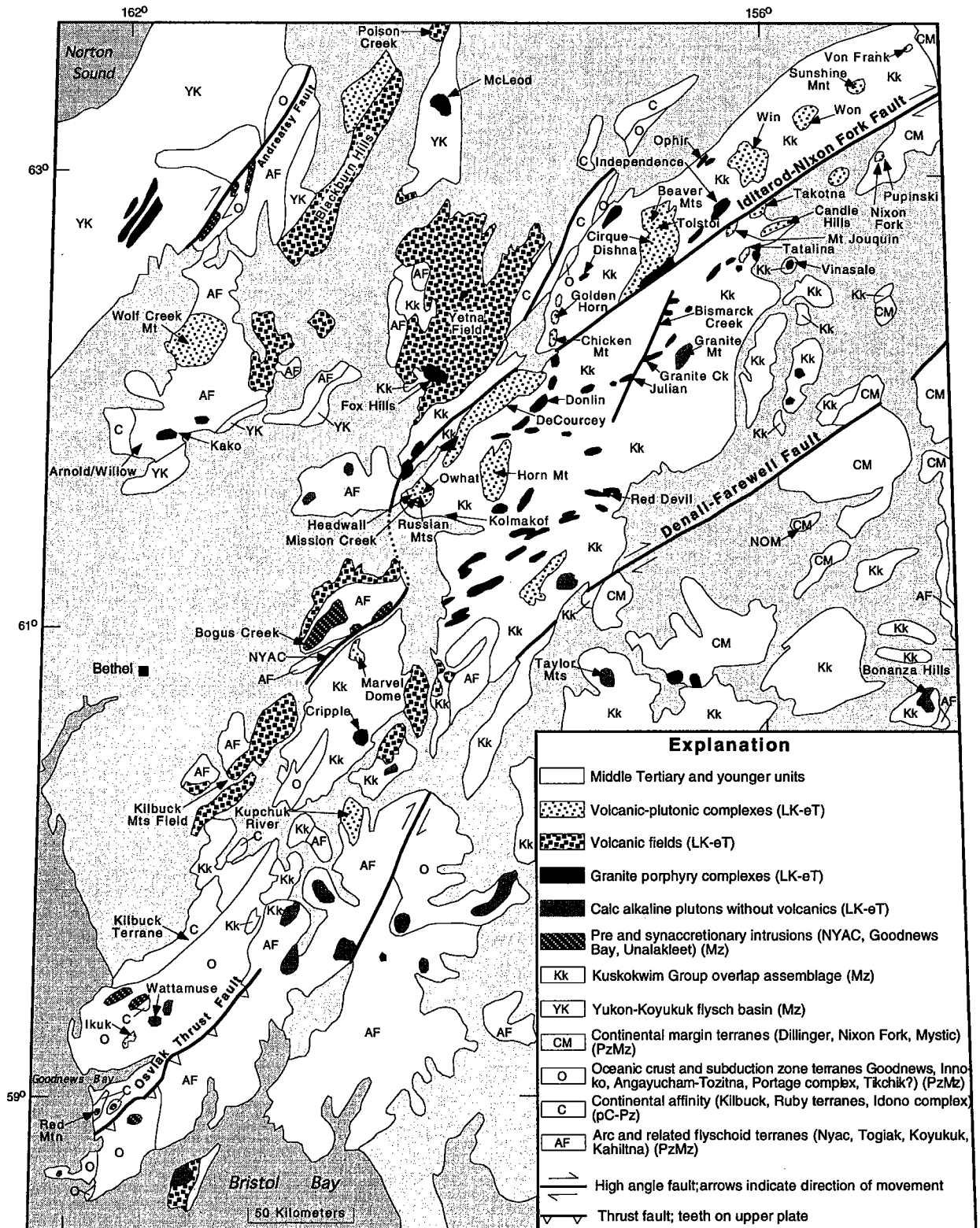


FIG. 2. Regional geology of southwestern Alaska, showing distribution of pre-, syn-, and postaccretionary geologic units, Late Cretaceous-early Tertiary igneous complexes, and names of the significant precious metal-bearing mineral deposits of the Kuskokwim mineral belt that are discussed in this paper.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

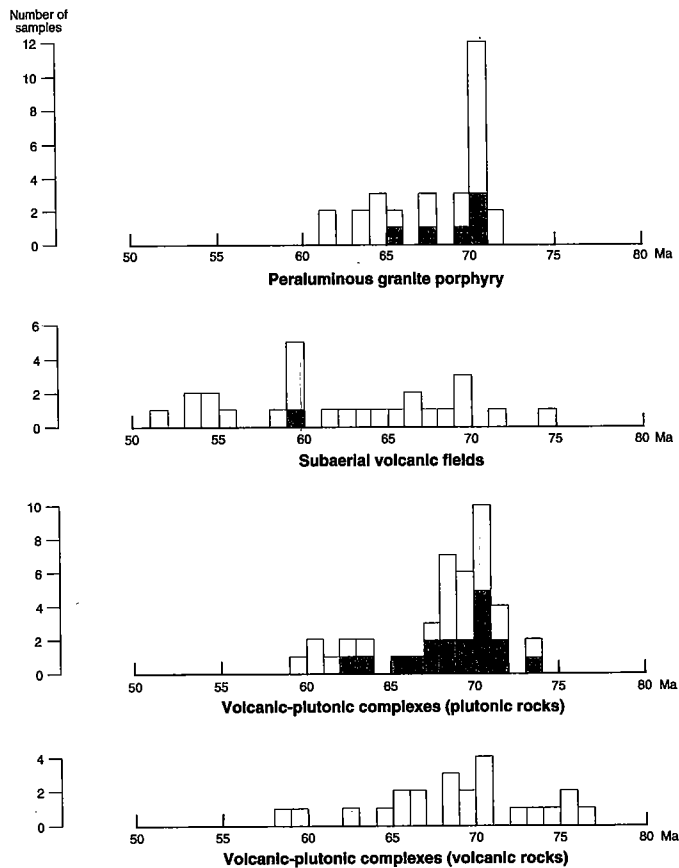


FIG. 3. Histogram summary of selected isotopic age determinations from Late Cretaceous-early Tertiary igneous rocks in the Kuskokwim mineral belt. Shading indicates age from a mineralized system. Most age determinations are by conventional K-Ar method. However, six determinations (four subaerial volcanic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

Description of Late Cretaceous-Early Tertiary Igneous Rocks

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

Volcanic-plutonic complexes

At least a dozen volcanic-plutonic complexes intrude the Kuskokwim Group in the area examined (Fig. 2). The largest and best exposed of these igneous complexes occur in the Beaver Mountains of the north-central Iditarod quadrangle and in the Russian, Horn, Chuilnik, and Kiokluk Mountains of the Sleetmute quadrangle. Other, smaller volcanic-plutonic complexes are found at Twin, Cloudy, Page, and Von Frank Mountains in the Medfra quadrangle; the Candle Hills in the McGrath quadrangle; at Takotna Mountain, Mount Joaquin, Chicken Mountain, and Granite Mountain in the Iditarod quadrangle; at Marvel Dome and Kupchuk River in the Bethel quadrangle; and at Wattamuse and Ikuk in the Goodnews quadrangle (Fig. 2). Geologic mapping has shown that slightly older volcanic rocks are intruded by comagmatic high-level intrusions. The volcanic-plutonic complexes of the Kuskokwim mineral belt range in size from the 650-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 Chuilnik and Kiokluk Mountains volcanic-plutonic complexes south of Sleetmute (Figs. 1, 2) have yielded a similar age range of 75 to 64 Ma (Reifenstuhl et al., 1984; Miller et al., 1989; Decker et al., 1995). Volcanic components of the Horn Mountains (Sleetmute quadrangle) and Russian Mountains (Russian Mission quadrangle) volcanic-plutonic complexes have, to date, yielded only Late Cretaceous isotopic ages (Bundtzen and Laird, 1991; Bundtzen et al., 1993).

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

Calc-alkaline plutons without volcanic rocks

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

Subaerial volcanic rocks

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

Peraluminous granite-porphyry dikes, stocks, and sills

Peraluminous granite-porphyry dikes, stocks, and sills are volumetrically minor but form important and distinct rocks in the study area. The dominant composition is granite or alkali quartz granite; however, minor amounts of granodiorite and quartz monzodiorite also exist in the suite (Fig. 4). These intrusions are peraluminous and corundum normative and commonly contain garnet phenocrysts. Available K-Ar and 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.

Petrogenesis of Late Cretaceous-early Tertiary igneous rocks

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

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

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

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

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

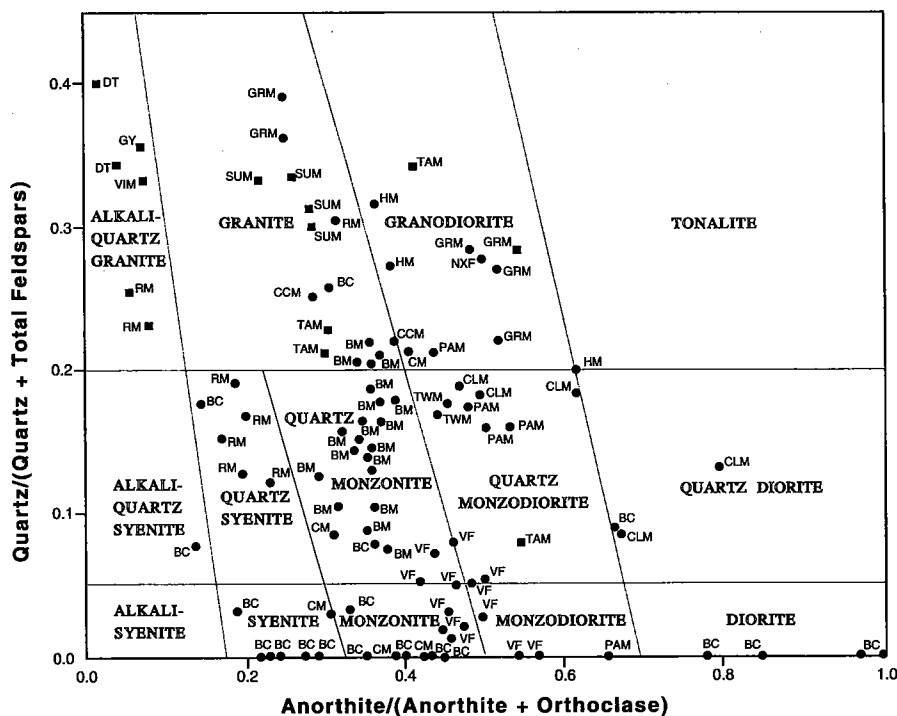


FIG. 4. Normative QAPF diagram, after Streckeisen and LeMaître (1979), of selected Late Cretaceous-early Tertiary plutonic rocks associated with gold-silver mineralization from the Kuskokwim mineral belt of southwest Alaska. Data from Moll et al. (1981), Bundtzen and Laird (1983b, 1991), Bull (1988),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

et al. (1988) for determining gold favorability. Keith and Swan (1987) first suggested that the oxidation state of a pluton influences its gold-bearing potential and concluded that a low oxidation state indicated gold-favorable conditions. Mishin and Petukhova (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 $\text{Fe}_2\text{O}_3/\text{FeO}$ 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-porphry at Donlin Creek, Vinasale Mountain, and the Ganes-Yankee Creek dike swarm plot mainly in the unfavorable field, even though these oxidized, granite-porphry 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-porphry 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-porphry suite described in this paper.

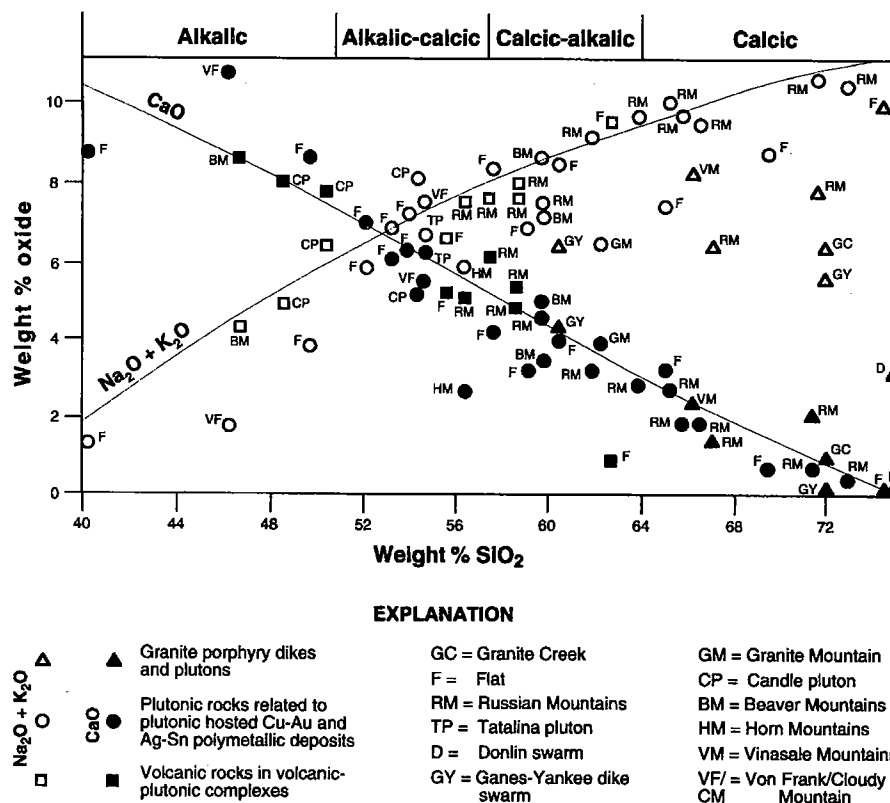


FIG. 5. Classification of volcanic and plutonic rocks from selected mineralized Late Cretaceous-early Tertiary igneous complexes in the Kuskokwim mineral belt, using the alkali-lime index of Peacock (1931). Volcanic-plutonic complexes generally plot in the alkali-calcic field; granite-porphyry complexes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

Economic Geology

Classification scheme for Late Cretaceous-early Tertiary metallogeny

Mineral deposits associated with igneous rocks of the Kuskokwim mineral belt are characterized by their alteration, metal content, mineralogy, detailed geologic setting, age, and trace element and isotopic data. Five major groups of mineral deposit types are summarized in this paper: (1) plutonic-hosted copper-gold polymetallic stockwork, skarn, and vein deposits, (2) peraluminous granite-porphyry-hosted gold po-

lymetallic deposits, (3) plutonic-related, boron-enriched silver-tin polymetallic mineralization in breccia pipes and as replacement deposits, (4) gold and silver mineralization associated with epithermal systems, and (5) gold polymetallic heavy mineral placer deposits. Table 2 lists the major precious metal-bearing deposits of the Kuskokwim mineral belt, divides them by deposit type, lists principal commodities present in each deposit, and provides resource grade and size estimates where available. None of the deposits has been completely explored.

Other mineral deposits associated with the Late Creta-

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

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

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

¹ Localities in Figure 2

² Calculated using $-1.42 \times 10^{-10} \text{ yr}^{-1}$ and age = 70 Ma

