# EXPLORATION MODELS FOR MID AND LATE CRETACEOUS INTRUSION-RELATED GOLD DEPOSITS IN ALASKA AND THE YUKON TERRITORY, CANADA

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## Abstract

Several major plutonic-related gold deposits are among a band of mineral occurrences extending from southwestern Alaska into the Yukon Territory, Canada, called the Tintina Gold Province (TGP). Current gold resources in Alaska and the Yukon Territory have increased from approximately 1 million ounces in 1985 to over 70 million ounces in 1999, with more than half of these resources occurring in the TGP.

Rb-Y-Nb concentrations from plutonic rock samples indicate most of this gold mineralization is due to arc-related magmatic belts of two separate age suites: ~88 to 110 Ma and ~65 to 70 Ma. Because the mid Cretaceous plutons are related to a subduction event along the Denali fault, Fort Knox, Pogo, Ryan Lode or True North direct analogues are not likely to be found south of the Denali fault. Conversely, the 65-70 Ma subduction-related plutons and related deposits can be found on either side of the Denali fault due to a more southerly subduction zone. Paleo-placement of the magmatic suites relates deposits now separated up to 450 kilometers from one another, and shows areas of favorable gold exploration, particularly where pluton density is high and where the mid and Late Cretaceous regions overlap.

Extensive multi-element assay data have been compiled from more than 10 of the TGP deposits for systematic comparison with respect to mineralization age, depth of emplacement, and proximity to causative pluton. Bismuth, gold and arsenic are the three most closely linked metals of these deposits, and variations in their statistical correlations and ratios change systematically with respect to depth of emplacement and proximity to a causative pluton. We show that the correlation between Bi and Au (as well as the Bi:Au ratio) systematically increases with depth of emplacement and proximity to a causative pluton. Average Bi:Au ratios range from 31:1 for deeper and more proximal deposits to 0.36:1 for shallower and more distal deposits. Bi vs. Au correlations range from $r = 0.89$ for deeper and/or more proximal deposits to $r = 0.12$ for shallower and/or more distal deposits. Conversely, the correlation between As and Au increases from $r = 0.23$ with deeper and/or intrusion-hosted deposits to $r = 0.86$ for shallower and/or more distal deposits. The change in As:Au ratios are much less predictable than Bi:Au ratios. Such variations in metal correlations and Bi:Au ratios may be used on a regional scale to target areas for exploration. Further, the Bi:Au ratio varies so systematically with respect to proximity to probable fluid sources that it may be possible to use it on a deposit scale to model the direction and path of fluid transport, and hence, target new areas for drilling.

## Introduction

Several major plutonic-related gold deposits are among a band of mineral occurrences extending from southwestern Alaska into the Yukon Territory, Canada (Fig. 1). The outline of the mineral province generally conforms to the trace of the Tintina-Kaltag fault system to the north and the Denali-Farewell fault system to the south and has been informally called the "Tintina gold belt." However, because it is comprised of several separate mineral belts, we refer to it as the "Tintina gold province" (TGP) to avoid confusion (after Bundtzen et al., 2000).

The scope of this paper is restricted to the metallogeny of some of the larger plutonic-gold systems in the TGP; primarily of mid and late Cretaceous ages. Although metallogeny has previously been considered in various places in Alaska and the Yukon Territory, these models predate the discovery of many gold deposits in the TGP. Newly acquired isotopic, trace element and multi-element analyses for this study and other recent studies have been applied to previous metallogenic models. Radiometric ages and trace element data of mid and late Cretaceous magmatic suites were used in conjunction with tectonic models to rationalize the formation and placement of magmatic suites and deposits through time.

Over the past 15 years most of the gold exploration in the Yukon and Alaska has been directed toward plutonic-related deposits of two age groups, ~88 to 110 Ma (e.g. Illinois Creek, Fort Knox, Pogo, Ryan Lode, Dublin Gulch, Brewery Creek, etc., Fig. 1) and ~70 to 65 Ma (e.g. Donlin Creek, Golden Zone, Mount Nansen, Casino, etc., Fig. 1). Our objective is to provide an explanation for the origin of these deposits, demonstrate their probable placement at the time of their origin, and to tie metal signatures to emplacement depth and distance from a causative pluton, both of which are expressed by pressure estimates and host rocks. The placement of deposits at the time of their origin illustrates regions possible for direct analogous types of gold deposits. The comparison of geochemistry from known deposits provides a model for identifying district-scale favorability as well as fluid source and path modeling for an individual deposit.

With few exceptions (e.g. Illinois Creek), the mid and late Cretaceous deposits dealt with in this paper have $^{87}Sr/^{86}Sr$ isotopic and/or Rb-Y-Nb trace element signatures consistent with subduction arc generated magmas (Fig. 2). The Illinois Creek deposit, is presented as the only known example of a collisional plutonic-related gold deposit of mid Cretaceous age in the TGP (Flanigan, 1998). To illustrate regional favorability, we have chosen to describe these deposits in relation to their magmatic suites for which they

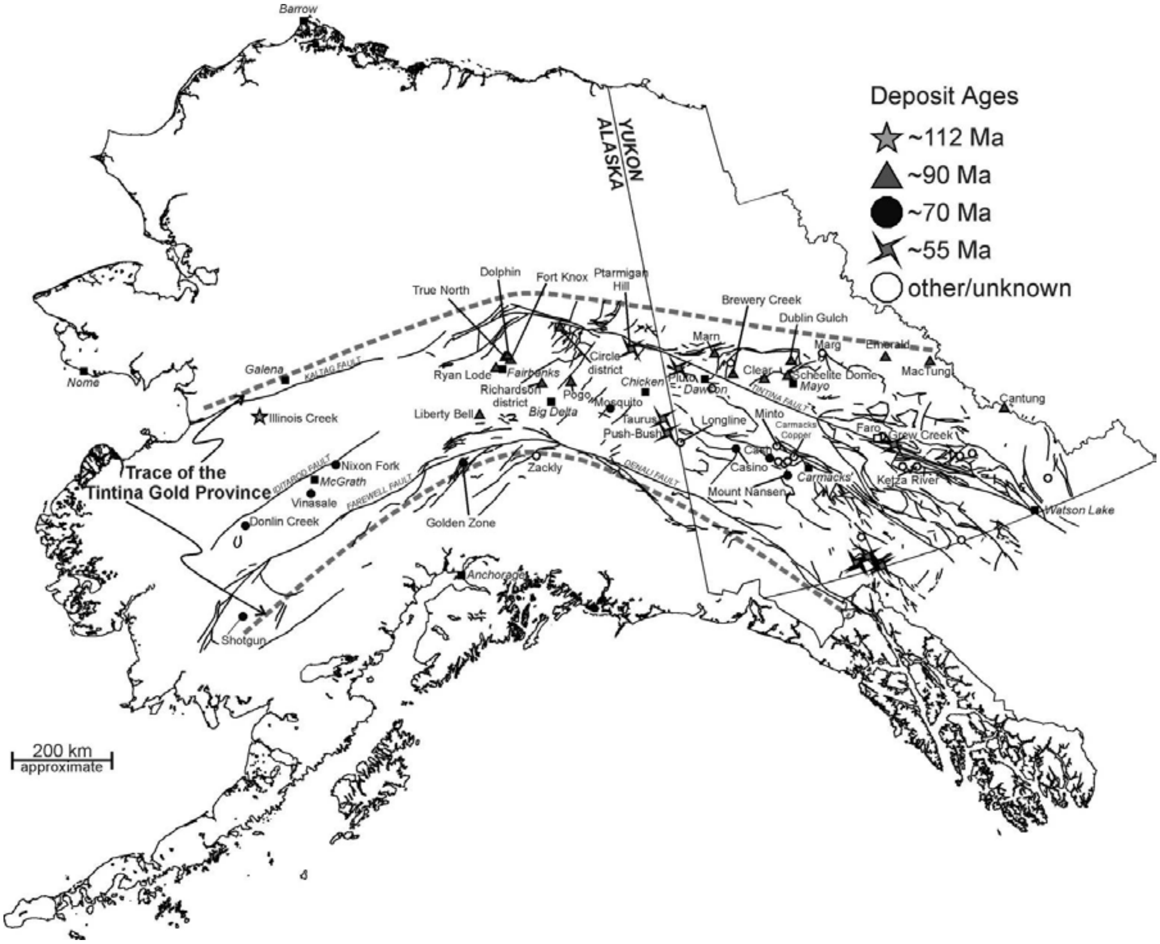

Figure 1: Present day locations of several gold occurrences and major faults with respect to the Tintina Gold Province boundary (dashed lines). Major faults in Alaska derived from Beikman, (1980). Major faults in the Yukon derived from Wheeler and McFeely (1991).

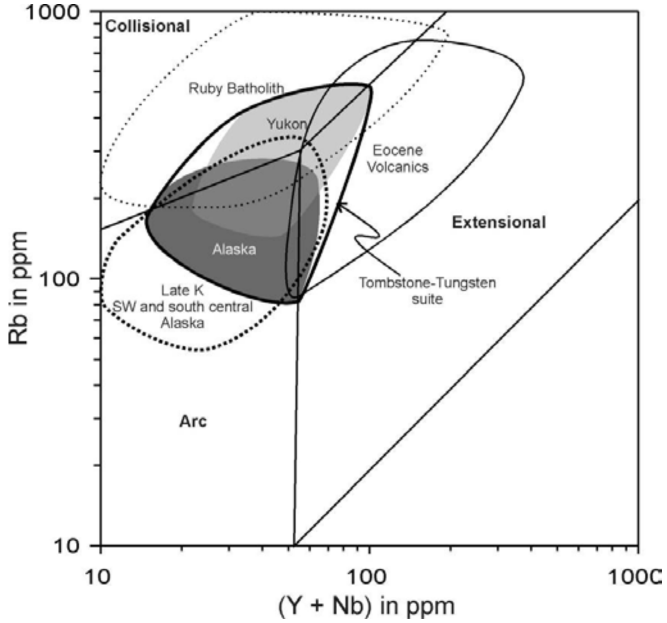

Figure 2: Rb-(Y + Nb) discriminant diagram showing fields for different suites of intrusive rock in Alaska and the Yukon. Based on data from Szumigala (1993, 1996), Gordey and Anderson (1993), Newberry and Solie (1994), Newberry and McCoy (1997), Duncan (1999), and Baker et al. (1998). Diagram after Pearce et al. (1984).

owe their genesis rather than previously defined mineral belts, which are more geographical. There are numerous deposits not discussed in this paper which have been described in some detail relating to smaller mineral belts, such as the Kuskokwim and east-central Alaska belts. For a comprehensive description of these belts and their deposits we refer the readers to Nokleberg et al. (1994, 1995 and 1996), Bundtzen et al. (1997, 2000), Goldfarb (1997), Young et al. (1997) and McCoy et al. (1997).

Because the major gold deposits we describe in this paper are inferred to be arc pluton-related it is no surprise that the location of these deposits are largely irrespective of sedimentary and metamorphic terranes and greatly influenced by paleo-subduction boundaries and offsets along major lateral faults. Two continental scale structures, the Tintina and Denali fault systems, reflect major tectonic activity indirectly associated with most of the mid and late Cretaceous gold mineralization in the Yukon Territory and adjacent Alaska. Although these fault systems are not directly responsible for the gold deposits, lateral motion along these faults has translated the position of many gold deposits 100's of kilometers from their place of original formation.

Large-scale regional faults are numerous in Yukon and Alaska and are important in both lateral and vertical juxtapositioning of blocks (Solie et al., 1995 and Newberry et al., 1998). These faults may or may not host gold, depending on their age and the presence of a mineralizing fluid source. Plutonic-related gold deposits in the Yukon and Alaska represent many different levels of exposure due to block faulting and subsequent erosion (McCoy et al., 1997 and O'Dea, 2000). Subtle differences in metal zoning of these deposits have been documented and reflect depth of deposit formation and/or distance from a causative pluton (this study). In Alaska, large-scale northeast trending high-angle normal block faults play a primary role in the depth of bedrock exposure and hence the type of gold deposit that can be exposed at the current erosional surface. In Yukon, analogous large-scale northeast trending faults generally are not recognized. However, in the Scheelite Dome area (Yukon) north-south normal faults have been documented in recent mapping, showing evidence for block faulting (O'Dea, 2000). In both Alaska and Yukon, voluminous volcanic rocks, small intrusive stocks, and dikes typically exemplify shallow exposures (<2 km). Large intrusion exposures of batholithic proportions and a paucity of volcanics is indicative of much deeper exposures (>4 km). However, significant uplift between magmatic events, scale of magmatism, or unresolved structure can complicate this simplified interpretation.

In this paper we present selected summaries of gold deposits related to the mid and Late Cretaceous magmatic suites followed by a simplified tectonic reconstruction showing probable displacements of these magmatic suites and their deposits. The paper concludes with a metal zoning model from data acquired from 13 of the selected deposits and implications for future exploration.

## Descriptive Summaries of Selected Tintina Gold Province Deposits

### Ruby Batholith Related Deposits (112-100 Ma)

**Illinois Creek (0.6 Moz):** Illinois Creek is a distal intermediate depth intrusion-related Au-Ag deposit in west central Alaska (Fig. 1). Mineralization at Illinois Creek is hosted in a deeply weathered and supergene oxidized shear (Flanigan, 1998). The shear strikes east-west and dips to the south at about 60$^{o}$. Hydrothermal fluids derived from the nearby 111-112 Ma collisional Khotol granite/granodiorite mineralized the quartz-carbonate metasediments fractured within the shear (Flanigan, 1998). The Khotol pluton marks the southernmost exposure of the 8000 km$^2$ Ruby batholith, the rest of which outcrops north of the Kaltag fault to just south of the Brooks Range. Subsequent to primary mineralization, percolation of meteoric water through the shear oxidized the sulfides almost entirely, leaving a massive iron and manganese gossan with gold and other precious metals. The country rock surrounding the shear is essentially non-mineralized, except for a short distance along a few permeable calcareous layers on the hanging wall side of the shear.

Although most of the ore minerals are secondary due to weathering, some primary sulfides have been identified in thin-section including pyrite, arsenopyrite, chalcopyrite, stannite, stibnite, boulangerite, pyrrhotite, galena, tetrahedrite, native Bi, bismuthinite, $(Bi, Sb)_2S_3$, and electrum. Due to supergene enrichment and remobilization, simple bivariate plots reveal few correlations (Flanigan, 1998). However, from a deposit-wide view of elemental contours, Au correlates well with As, Ag, Bi, Sb, Pb, and Cu; somewhat well with Fe and Mn; very poorly with Zn; and inversely with Ca and Mg (Flanigan, 1998). Bismuth concentrations typically range from 10 ppm to over 10,000 ppm in a few drill intercepts. Based on data from Flanigan (1998), Bi concentrations in the hundreds and thousands of ppm occur within or very near the highest gold grade ore zones. Average ratios are Bi:Au = 87:1, Ag:Au = 23:1, As:Au =3745:1, Pb:Au = 870:1, and Sb:Au = 443:1 (this study).

Arsenopyrite thermometry and fluid inclusion thermometry/barometry indicates ore mineralization temperatures of 300 ±25$^{o}$C and pressures of 1.3 ±0.4 kb (Flanigan, 1998).

### Mid Cretaceous Arc Related Deposits (88 to 110 Ma)

**Fort Knox (7.2 Moz):** Fort Knox is a deep level, intrusion-hosted Au deposit in the Fairbanks mining district, Alaska (Figs. 1, 3 and 4). Mineralization at Fort Knox is almost completely confined to the 92 Ma Fort Knox pluton, a composite granitic body comprised of equigranular hornblende-biotite granite, medium grained porphyritic granite, and coarse-grained, seriate, hornblende-biotite granite/granodiorite (Bakke, 1995, Bakke et al., 2000 and Newberry et al., 1995). The majority of the gold occurs within the main granitic body where it is dissected by west-northwest trending, high angle stockwork veins, shears, pegmatite/aplite dikes, and lower angle sheeted, shear-hosted quartz veins.

Gold mineralization is relatively low in sulfides (<1%), but generally associated with pyrite, arsenopyrite, bismuthinite, tellurobismuthite, scheelite, and molybdenite. While propylitic alteration is pervasive throughout the intrusion, potassic, albitic, and sericitic alteration appear to be restricted to mineralized zones (Bakke, 1995 and Bakke et al., 2000). Gold strongly correlates with Bi and Te (Bakke, 1995, this study, Fig. 5). Although W, Mo, Sb, and As minerals are common in ore zones, their correlations with Au are weak (this study). Fort Knox lacks appreciable Hg, Cu, Pb, and Zn.

Fluid inclusion thermometry/barometry indicate mineralization temperatures of 305 ±25$^{o}$C and pressures of 1.25 to 1.5 kb (McCoy et al., 1997).

**Pogo (5.2 Moz):** Pogo is a deep-level, proximal intrusion-related deposit in east-central Alaska (Figs. 1 and 4). Mineralization at Pogo formed under ductile conditions and occurs in gently dipping, subparallel quartz bodies along favorable permeable horizons. Brittle structures are found only as stockwork veining where the replacement bodies come in contact with dikes (Smith et al., 1999, 2000). The replacement bodies are mostly quartz primarily hosted in amphibolite facies gneiss approximately 1.5 miles south of the mid-Cretaceous (93.7 Ma) Goodpaster Batholith (Smith et al., 1999, 2000). The mineralized zones contain about 3% ore minerals, including pyrite, pyrrhotite, loellingite, arsenopyrite, chalcopyrite, bismuthinite, various Ag-Pb-Bi±S minerals, maldonite, native bismuth, and native Au (Smith et al., 1999, 2000).

Alteration in the mineralized zones occurs as early biotite and quartz-sericite-stockwork, and sericite-dolomite. This alteration assemblage is characteristic of both vein and

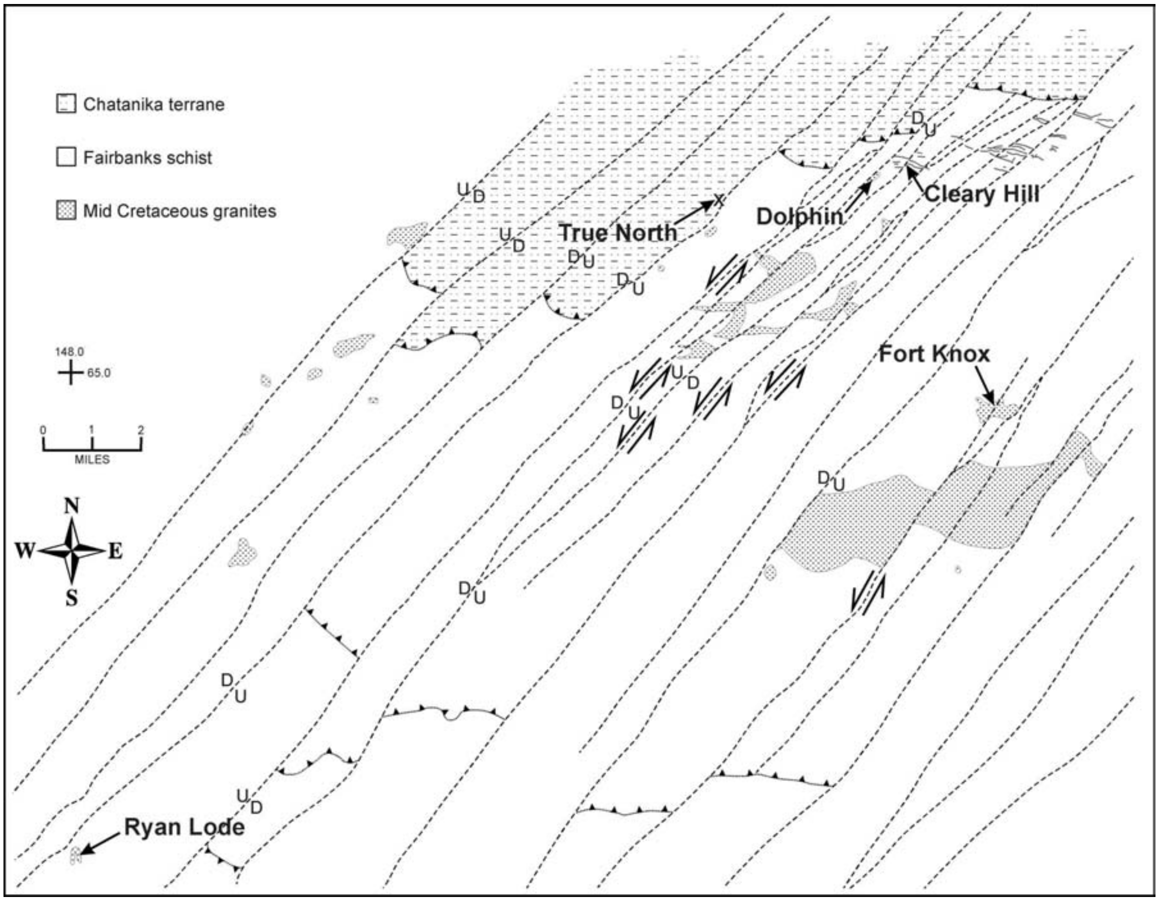

Figure 3: Plan map of the Fairbanks mining district showing deposit locations and high angle northeast trending faults responsible for different exposure levels. Map after Newberry et al. (1996)

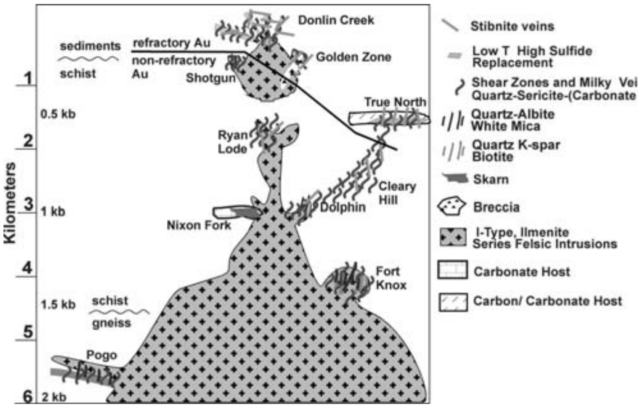

Figure 4: Cross section schematic of modeled depth of emplacement for many mid and Late Cretaceous plutonic-related deposits in Alaska. After McCoy et al. (1998).

replacement-type mineralization. Gold strongly correlates with Bi and shows a lesser correlation with other metals (Smith et al., 1999, Fig. 5).

Fluid inclusion studies and arsenopyrite thermometry (McCoy et al., 1998) indicates high mineralization temperatures (310 to 640$^{o}$ C) and pressures indicative of deep emplacement (~6-7 km).

**Ryan Lode (2.4 Moz):** Ryan Lode is a proximal and intrusion-hosted intermediate level Au deposit in the Fairbanks district, Alaska (Figs. 1, 3 and 4). Mineralization at Ryan Lode is shear-hosted and occurs in both the intrusion and the surrounding amphibolite grade pelitic schist. The 90 Ma pluton is comprised of equigranular, hornblende-biotite granodiorite, porphyritic biotite granite, and intrusion breccia of fine-grained granodiorite with clasts of schist (Newberry et al., 1995 and Bakke et al., 2000). Gold mineralization is primarily associated with variably granulated quartz veins, gouge, and tectonic breccia within the shear zones.

Gold mineralization is high sulfide (>1%) including arsenopyrite, stibnite, sphalerite, chalcopyrite, molybdenite, boulangerite, and Pb-Bi sulfosalts (Newberry et al., 1995). Scheelite also is common within the mineralized zones. Arsenopyrite is the predominant sulfide and occurs in higher percentages with the quartz-calcite veins (1-10%). Stibnite is less abundant than arsenopyrite (≤1%) and is paragenetically later (Newberry et al., 1995). Molybdenite and scheelite occur almost exclusively in the intrusion-hosted shear in trace amounts. Propylitic alteration is pervasive, but weak in the intrusion. Albitic alteration is restricted to small centimeter sized envelopes about quartz veins in the albite flooded areas. Sericite alteration occurs throughout the porphyritic intrusion, but is most intense in the gold-bearing shear zones.

Gold mineralized zones contain high concentrations of Bi, Te, As, and Sb, and low Cu, Pb, Zn. Bi and As strongly correlates with Au (this study, Figs. 5 and 6).

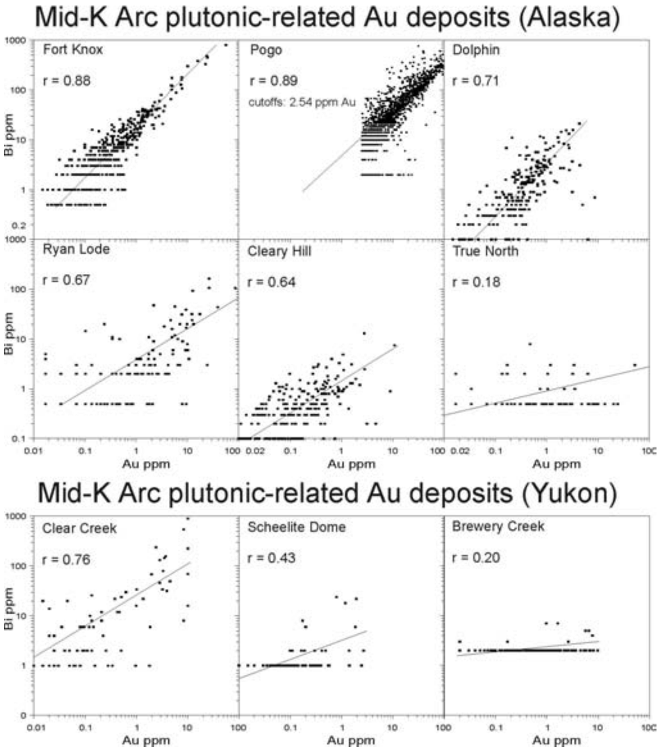

Figure 5: Bi vs. Au scatter plots for mid Cretaceous arc plutonic-related deposits in interior Alaska, and the Yukon Territory, Canada. Plots show Bi vs. Au correlations increasing with depth of deposit emplacement and/or proximity a causative pluton. Data sources: Arne Bakke and John Odden of Kinross, written communication (1999); Smith et al. (1999); John Royall/International Freegold, written communication (1999); Marsh et al. (1999); John Mair, written communication (1999); and Mark Lindsay, written communication (1999).

**Dolphin (1.5 Moz):** Dolphin is an intrusion hosted, intermediate-level Au deposit in the Fairbanks district, Alaska (Figs. 1, 3 and 4). Mineralization at Dolphin occurs within a small 91 Ma granodiorite/tonalite stock (McCoy et al., 1997). The mineralization is structurally controlled along fractures and a high angle shear of speculative strike (east-west) as millimeter to centimeter thick quartz±carbonate±albite veins (Adams et al., 2000). Typical gold mineralization includes arsenopyrite, pyrite, stibnite, boulangerite, maldonite ($Au_2Bi$), tetradymite, tetrahedrite, galena, and sphalerite. Sericite alteration occurs throughout the stock, but is most intense in highly fractured areas where veining dominates. The sericite generally occurs as centimeter-scale halos around hairline to centimeter thick quartz±carbonate±albite veins.

Dolphin is highly anomalous in Au, moderately anomalous in As, Sb, Ag, and Pb, and weakly anomalous in Bi and Te. Gold carries a strong correlation with Bi, As (this study, Figs. 5 and 6). Silver, Pb and Zn are common throughout the ore zones but have a poor overall correlation with Au and are attributed to a hydrothermal event later than the 90 Ma main-stage mineralization (McCoy et al., 1998). Gold occurs as free grains in quartz and as inclusions in high temperature arsenopyrite (Adams et al., 2000).

**Cleary Hill:** Cleary Hill is an intermediate level, distal, plutonic-related gold deposit in the Fairbanks mining district, Alaska (Figs. 3 and 4). High-grade, mesothermal gold-quartz veins hosted in Fairbanks schist characterize mineralization (Hill, 1933). $^{40}Ar/^{39}Ar$ spectra of hydrothermal sericite give a plateau age of 88 Ma coeval with late stage mineralization of the nearby Dolphin deposit (McCoy et al., 1998). Gold associated minerals include arsenopyrite, stibnite, jamesonite, and lesser tetrahedrite, pyrite, and galena. Although the deposit is recognized for it past production of the high-grade ore, considerable disseminated gold typically envelopes the high grade veins. Mineralization is generally comprised of sericite altered and highly silicified quartz mica schist that has been fractured and contains millimeter scale quartz veinlets with sulfides. The geometry of the deposit is a generally east-west shear that dips about 60 degrees to the south.

Temperature and pressure estimates from fluid inclusion analyses indicate a temperature of about 300$^{o}$ C and a pressure of 0.9 kb (Metz, 1991). Bi and As show a moderate to strong correlation with Au (this study, Figs. 5 and 6).

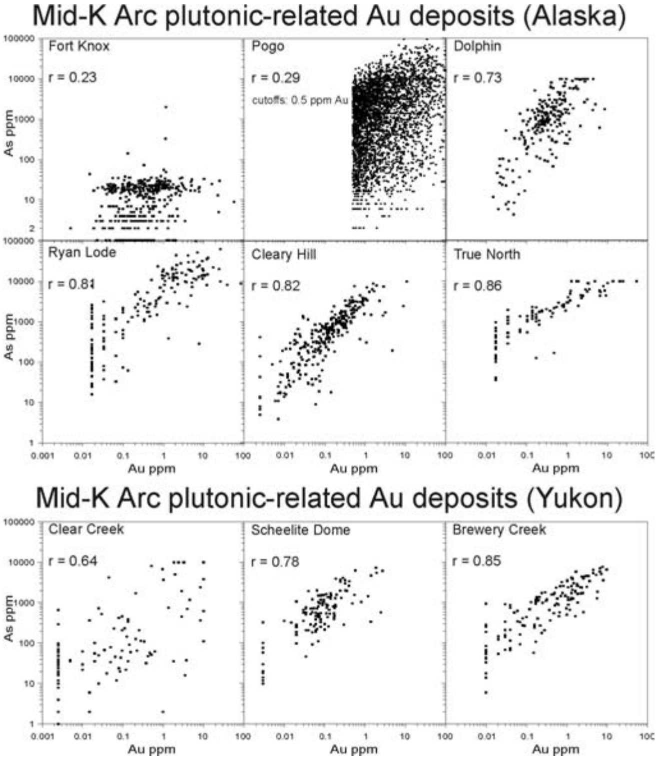

Figure 6: As vs. Au scatter plots for mid Cretaceous arc plutonic-related deposits in interior Alaska, and the Yukon Territory, Canada. Plots show As vs. Au correlations decreasing with depth deposit emplacement and/or proximity to a causative pluton. Data sources: Arne Bakke and John Odden of Kinross, written communication (1999); Smith et al. (1999); John Royall/International Freegold, written communication (1999); Marsh et al. (1999); John Mair, written communication (1999); and Mark Lindsay, written communication (1999).

**True North (1.3 Moz):** True North is an intermediate-level, distal, plutonic-related deposit in the Fairbanks district, Alaska (Figs. 1, 3 and 4). Mineralization is structurally and chemically controlled and primarily flat-lying (Masterman et al., 1995). The bulk of the gold mineralization is confined to a shallow dipping horizon of fractured calcareous and carbonaceous schist bounded on the top by Chatanika terrane eclogite. The horizon is intersected by several northeast-trending, northwest dipping faults and shears, which also are mineralized and presumed to have acted as feeders to the flat lying horizon. The mineralizing fluids are believed to have been derived from an underlying ~90 Ma Pedro Dome, Fort Knox, or Dolphin granodiorite equivalent (Bakke et al., 2000).

The major ore minerals include pyrite, arsenopyrite, and stibnite. Anomalous metals include Au, As, Sb, Ag, Hg, and Bi. Gold has a strong correlation with As, a moderate correlation with Sb, and a weak correlation with Ag, Hg, and Bi (this study, Figs. 5 and 6).

**Brewery Creek (0.6 Moz):** Brewery Creek is a shallow-level intrusion and siliciclastic-hosted deposit situated on the north side of the Tintina fault in the Yukon Territory (Fig. 1). The deposit is hosted in Cretaceous monzonite sills (91.5 Ma) in Devonian aged Earn Group siliciclastic rocks of the Selwyn Basin (Diment and Craig, 1999 and Lindsay et al., 2000). Mineralization is controlled by northeast and northwest trending high angle shears and south dipping listric normal faults. Sills and listric structures are controlled by pre-existing thrust faults. Gold occurs in submicron form in solid solution with pyrite and arsenopyrite and as growth bands around larger sulfide grains (Diment and Craig, 1999). Mineralization is hosted in thin quartz veinlets and is associated with district scale antimony, arsenic and mercury anomalies. Gold strongly correlates with As (this study, Fig. 6).

**Dublin Gulch (1.5 Moz):** The Dublin Gulch area encompasses about two dozen stocks located about 50 km north of Mayo, Yukon (Fig. 1). The Dublin Gulch intrusion is the most economically important stock, comprised dominantly of equigranular granodiorite to quartz monzonite (Hitchins and Orssich, 1995). Mineralization of the Dublin Gulch stock bares a strong resemblance to the Fort Knox deposit in Alaska. Mineralization occurs in sheeted quartz veins, quartz-sulfide fissure veins, scheelite skarn, and tin-tourmaline breccias (Hitchins and Orssich, 1995).

At the Eagle Zone, subparallel, sheeted quartz veins occur within the intrusion. The veins are milky white or clear gray and typically 1 to 2 cm in width (Hitchins and Orssich, 1995). Ore minerals within the veins include arsenopyrite, pyrrhotite, chalcopyrite, bismuthinite, tetradymite, tellurobismuthite, native bismuth, and rare molybdenite (Hitchins and Orssich, 1995). Gold grains occur as complex intergrowths with native bismuth and a strong correlation occurs between Au, Bi, and Te (Hitchins and Orssich, 1995).

Fluid inclusion thermometry/barometry indicates mineralization temperatures of 200 to 350$^{o}$C and pressures >1.5 kb (Smit et al., 1996 and Lang et al., 2000).

**Clear Creek:** The Clear Creek area is located about 50 kilometers north-northwest of Stewart Crossing, Yukon Territory (Fig. 1), and contains six plutons of the Tombstone suite, Rhosgobel, Big Creek, Pukelman, Saddle, Eiger, and Josephine stocks. The stocks are comprised of granite, rhyolite, quartz monzonite, granodiorite, and diorite (Marsh et al., 1999). U-Pb ages of these intrusions average ~92 Ma (Murphy, 1997). Dikes are also common to the Clear Creek area and they are typically comprised of rhyolite, granite quartz-feldspar porphyry, pegmatite, aplite, and lamprophyre (Marsh et al., 1999). Gold mineralization is intimately associated with these stocks (excluding Big Creek) as sheeted veins within the margins of the stocks and adjacent hornfels, irregularly spaced quartz veins in hornfels, and tungsten skarn (Marsh et al., 1999). The stocks and hornfels are cut by the dikes, which are in turn cut by the sheeted veins (Marsh et al., 1999). Thus, it is presumed that mineralizing fluids are associated with the latter phases of magma crystallization. Overall, Au correlates well with Bi, As, and Te and Ag shows a moderate to strong correlation with Bi, Te, Pb, and Sb (this study, Figs. 5 and 6).

**Scheelite Dome:** The Scheelite Dome area is located northwest of Mayo, Yukon Territory (Fig. 1). Gold mineralization is hosted within the 91 Ma Scheelite dome stock (biotite and hornblende-bearing granite) and adjacent upper Proterozoic-lower Cambrian metasedimentary rocks of the Hyland Group as structurally controlled metasediment-hosted quartz-sulfide veins, skarn, granite hosted low sulfide veins, and replacement-type occurrences (Hulstein and Zuran, 1999 and Mair et al., 2000). The metamorphic rocks, where most of the mineralization occurs, include muscovite-chlorite phyllites, quartzofeldspathic and micaceous quartzites (Hulstein and Zuran, 1999 and Mair et al., 2000). The regional foliation is cut by three sets of fault structures oriented east-west, northwest-southeast, and north-south. The north-south faults are rarely mineralized, have normal down-to-the-west displacement, truncate and offset east-west structures, and are presumed to be post-mineral (Hulstein and Zuran, 1999 and Mair et al., 2000). The east-west and northwest-southeast structures are commonly mineralized with auriferous quartz veins containing arsenopyrite, +/-stibnite, +/-galena, +/-pyrite. The veins occur as breccia veins up to several meters thick, to thin quartz veinlets filling joint sets, and as sheeted veins (closely spaced quartz veinlets). Analyses of fluid inclusions indicate mineralization temperatures of 240 to 350$^{o}$C and pressures up to 2.5 kb (Hulstein et al., 1999). Au strongly correlates with As, Bi, and Te (this study, Figs. 5 and 6).

## Late Cretaceous Magmatic Belt Deposits (70-65 Ma)

**Donlin Creek (10.1 Moz):** Donlin Creek is a shallow level, intrusion-hosted Au deposit in southwestern Alaska (Fig. 1). Mineralization at Donlin Creek is hosted in a 6-km-long 70 Ma rhyodacite porphyry sill complex intruding upper Cretaceous graywacke and shale (Ebert et al., 2000). Gold mineralization is structurally controlled within the dikes and sills (and directly adjacent country rock) occurring in quartz-carbonate veinlets, and disseminated zones in sericitized intrusions.

Ore minerals include early pyrite, arsenopyrite, chalcopyrite, and later native As, realgar, and orpiment accompanied by supergene As-Sb enrichment. Gold is most commonly associated with arsenopyrite, correlates very well with As (Ebert et al., 2000, this study, Fig. 7), and is lattice bound (refractory). Alteration includes pervasive sericite and carbonate with thin, wispy graphite. Silicification is rare.

Interpretation of fluid inclusion data (McCoy et al., 1999) suggest that early saline magmatic fluids (>550$^{o}$C) cooled and separated into gas and brine rich end members (<550°C and <0.5 kb) leading to early metal deposition. Subsequent influx of meteoric water decreased the temperature and/or increased $fS_2/fO_2$, leading to further metal deposition as well as late paragenesis to higher $fS_2$ mineral stability (native As, orpiment, realgar).

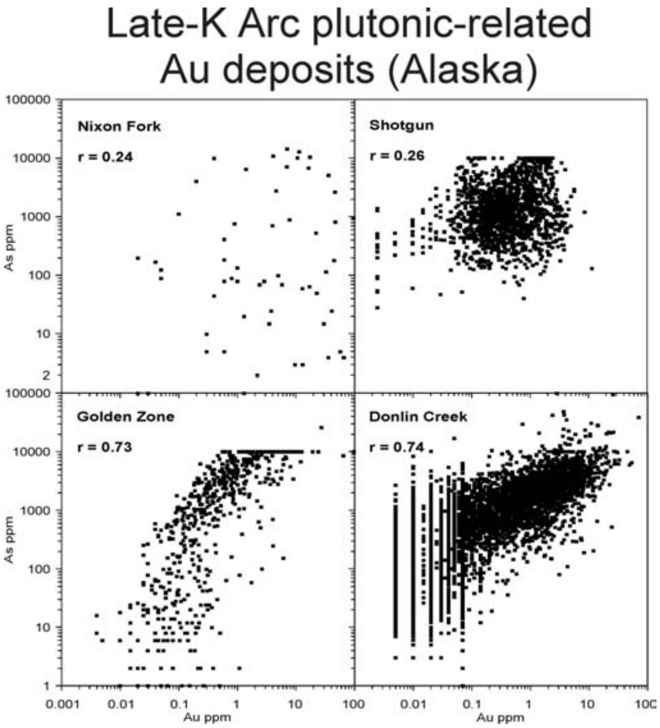

Figure 7: As vs. Au scatter plots for late Cretaceous arc plutonic-related deposits of south and southwest Alaska. Plots show As vs. Au correlations decreasing with depth of deposit emplacement and/or proximity to a causative pluton. Data sources: Rainer Newberry, unpublished data; Cameron Rombach and Greg Johnson/Novagold Resources, written communication (1999); Ben Gage, written communication (1999); and Lance Miller/Placer Dome Exploration, written communication (1999).

**Nixon Fork (0.1 Moz):** The Nixon Fork deposit is an intermediate level gold skarn deposit located in southwest Alaska (Figs. 1 and 4). The deposit is hosted by Ordovician limestone and dolomite (Herreid, 1966) near a 69 Ma, very reduced, quartz monzonite-quartz monzodiorite stock. The stock is cut by 69 Ma, quartz-sericite altered, gold-bearing porphyry dikes (Cutler, 1994); skarns seem to be focused near these dikes and are not uniformly distributed around the stock (Newberry et al., 1997). Detailed mapping and core logging has shown the presence of vertical skarn "pipes", with garnet-rich cores, garnet-pyroxene margins, and wollastonite-idocrase-scapolite rims, near the pluton margin (Newberry et al., 1997). Zoning is complicated by extensive dolomite-rich layers within limestone, which generate extensive sulfide-poor serpentine (after forsterite)-diopside-phlogopite-actinolite skarns, and by post-ore faults (Newberry et al., 1997). Historic production at Nixon Fork was from supergene enriched, clay-quartz rocks containing multiple oz/ton gold and several percent copper oxide/carbonate concentrations (Herreid, 1966). Present efforts are directed towards primary ores in sulfide-salite-rich skarn and lesser sulfide replacement bodies in limestone.

Gold mineralization occurs with pyrrhotite, pyrite, chalcopyrite, arsenopyrite and some joseite, bismuthenite, and bismuth identified by electron microprobe. Gold has a strong correlation with Bi and essentially no correlation with As (this study, Figs. 7 and 8). Sphalerite barometry performed by Cutler (1994) indicated a mineralization pressure of 1 kb.

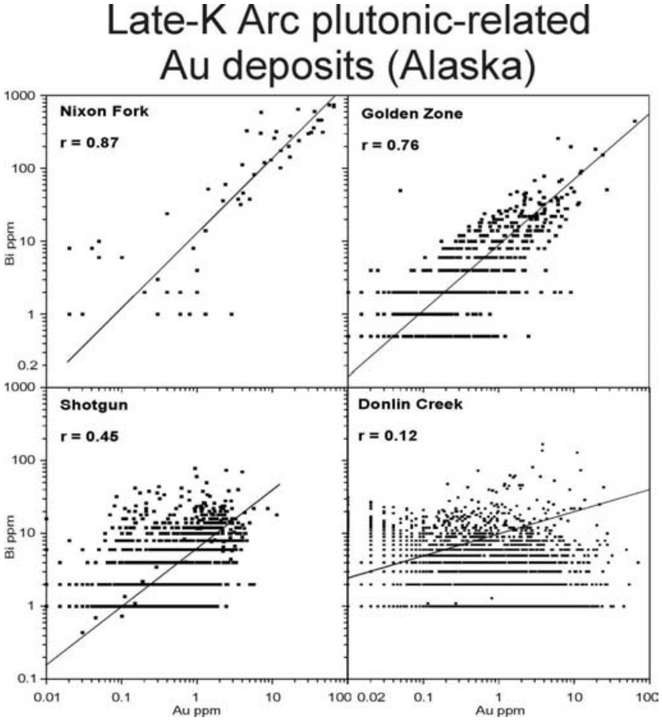

Figure 8: Bi vs. Au scatter plots for late Cretaceous arc plutonic-related deposits of south and southwest Alaska. Plots show Bi vs. Au correlations increasing with depth of deposit emplacement and/or proximity to a causative pluton. Data sources: Rainer Newberry, unpublished data; Cameron Rombach and Greg Johnson/Novagold Resources, written communication (1999); Ben Gage, written communication (1999); and Lance Miller/Placer Dome Exploration, written communication (1999).

**Shotgun (1.0 Moz):** Shotgun is a proximal intrusion-hosted Au deposit in southwestern Alaska (Fig. 1). Shotgun is classified as a gold porphyry deposit with Au-Cu-As quartz stockwork in a 70 Ma rhyolite (granite porphyry) stock and adjacent hornfels (Rombach, 2000). Ore zones are primarily high-density stockwork quartz veining and hydrothermal breccias within rhyolite. Unlike typical Cu-Mo porphyry deposits, which share many similarities, Shotgun is highly anomalous in Au and As and essentially lacks potassic alteration. At Shotgun the dominant alteration is albite-sericite-quartz±carbonate.

Ore minerals include hypogene native Au and Bi, Bi-Te minerals, arsenopyrite, chalcopyrite, loellingite, pyrrhotite, pyrite, scheelite, sphalerite, and supergene covellite, chalcocite, native Cu, and marcasite (Rombach, 2000). Gold at Shotgun occurs as free Au. Based on data from Rombach (1999, written communication), Shotgun is highly anomalous in Au, As, Ag, and Cu, and moderately anomalous in Bi and Mo. Overall, gold exhibits a strong correlation with Ag and a weak to moderate correlation with As, Cu, and Bi (this study, Figs. 7 and 8). However, Rombach (2000) found that in discrete drill holes Bi can exhibit a strong correlation with gold.

The high degree of brittle fracturing and stockwork veining suggest a low pressure, near surface emplacement. Rombach (2000) estimated temperatures from arsenopyrite and fluid inclusion thermometry between 450° to 600°C. Highly saline fluids in inclusions, identical $^{40}$Ar/$^{39}$Ar intrusive and mineralization ~70 Ma ages were also observed.

**Golden Zone (1.2 Moz):** The Golden Zone deposit is shallow-level intrusion-hosted deposit located just south of the Denali fault in south central Alaska (Fig. 1). Ben Gage (written communication, 2000) describes the deposit as being hosted in a 69 Ma, sub-vertical, monzodiorite porphyry stock that intrudes a shaley-chert and pebble conglomerate metasedimentary unit. The phenocryst assemblage is plagioclase, biotite and hornblende. Most of the mineralization occurs in a steeply dipping breccia-pipe, contained in the stock. The clasts are angular, sericite altered monzodiorite, and the matrix consists of quartz, carbonate and sulfides. The major ore minerals are arsenopyrite, pyrite, chalcopyrite, sphalerite and pyrrhotite and significant amounts of galena, Freibergite (Ag-rich tetrahedrite). Gold, Bi-minerals and Pb-sulfosalts have been identified in thin section and electron microprobe. Gold has a moderate to strong correlation with Bi and As (this study, Figs. 7 and 8). Alteration consists of minor potassic (biotite and K-spar) and quartz/sericite/carbonate, which is much more extensive. The deposit is diced up with pre- and post-mineralization high angle shears and joints sets.

**Casino (2.7 Moz):** The Casino deposit is located in the Dawson Range mountains in the west-central Yukon Territory (Fig. 1). Gold and copper mineralization is related to the breccia and microbreccia pipe of the 72 to 74 Ma Casino Intrusive Complex (Bower et al., 1995). The deposit contains a 300-meter thick supergene Cu-enriched cap overlying a hypogene sulfide zone which contains most of the gold. The Intrusive Casino Complex is comprise of latite and rhyodacite porphyry , quartz monzonite, intrusion breccia, and microbreccia (Bower et al., 1995). Ore minerals include chalcopyrite, pyrite, sphalerite, galena, tetrahedrite and some Bi minerals. Anomalous metals include Ag, As, Au, Bi, Cu, Cd, Mn, Pb, Sb, Zn, and W (Bower et al., 1995). Gold occurs as 50 to 70 micron sized grains in quartz and as 1 to 15 micron sized inclusions in fractures in pyrite and chalcopyrite (Bower et al., 1995).

**Mt Nansen (0.15 Moz):** The Mount Nansen property is a sub-volcanic feldspar porphyry intrusion of the late Cretaceous Mount Nansen volcanic complex (Stroshein, 1999). The property is located about 50 km west of Carmacks, Yukon (Fig. 1).

Precious metal mineralization consists of structurally controlled planer veins and pipe-like breccias peripheral to the central porphyry complex (Stroshein, 1999). Gold and silver-rich sulfide consists of pyrite, arsenopyrite, sphalerite, galena, sulfosalts, bornite, stibnite and chalcopyrite. Gold is apparently related to the early pyrite phase and occurs as 5 to 40 micron sized inclusions in the pyrite (Stroshein, 1999).

## Gold Producing Magmatic Events

**Ruby Batholith (112 to 100 Ma):** Based on Sr-Nd-Pb isotope and trace element studies, granitic rocks of the Ruby batholith (~111 Ma) are interpreted to be derived from the melting of lower crustal rocks during crustal thickening (Arth et al., 1989 and Miller, 1989). Data from these plutons plotted on a Rb-(Y + Nb) discriminant diagram (Fig. 2) indicates a collisional tectonic setting consistent with Miller's interpretation (Flanigan, 1998). This collisional event is apparently related to the opening of the Canada basin (Fig. 9). The Ruby batholith is comprised of highly evolved tin-granites and several tin placers are found in streams draining the plutons on the north side of the Kaltag fault. Additionally, many of these streams also show elevated concentrations of W, Au, Ag, Sb, Bi, and Te (Solie et al., 1993a, b). Ruby batholith plutons north of the Kaltag fault exhibit K-Ar ages from about 98 to 111 Ma (Miller, 1989). The Ray Mountains pluton yields zircon U-Pb dates from 109 to 112 Ma (Patton et al., 1987). The Jim River and Hodzana plutons give a Rb-Sr whole rock isochron age of 112 Ma (Blum et al., 1987). South of the Kaltag fault, in the Illinois Creek area, the Khotol pluton exhibits a K-Ar age of 112 Ma (Patton et al., 1984) and an $^{40}$Ar/$^{39}$Ar plateau age of 111 Ma (Flanigan, 1998). The younger K-Ar ages as compared to U-Pb zircon and $^{40}$Ar/$^{39}$Ar ages for the Ruby batholith may be indicative of thermal resetting during probable slow cooling of the magmas. Thus, many of the K-Ar ages for the Ruby batholith may be as much as 10 Ma younger than the age of emplacement.

The southern extension of the Ruby batholith (Khotol pluton) found south of the Kaltag fault is displaced about 150 km west of correlative granites north of the fault. Illinois Creek and other Au-Ag prospects are located at the southernmost end of the Ruby batholith (Fig. 9).

**Mid Cretaceous Magmatism:** Possibly the most significant group of mid Cretaceous intrusions with respect to gold deposits is the 88-110 Ma Tombstone-Tungsten suite. The Tombstone-Tungsten suite is a composite comprised of plutons from the Tombstone and the Tungsten suites. The Tombstone suite is a group of metaluminous, subalkaline to alkaline, mainly intermediate to felsic intrusions (Mortensen et al., 2000) dominantly located north of the Tintina fault in the Yukon and south of the Tintina fault in Alaska. The Tungsten suite intrusions are peraluminous and located up to 200 kilometers north of the Tintina fault in eastern Yukon. The Tungsten suite intrusions are of equivalent age to the Tombstone intrusions and likely represent more evolved magmas of the Tombstone suite. Other mid Cretaceous plutonic suites include the Selwyn, Cassiar, and Whitehorse suites (Wheeler and McFeely, 1991). K-Ar ages of these plutons range from 88 to 110 Ma in the Yukon (Mortensen, 1999), and 88 to 108 Ma $^{40}$Ar/$^{39}$Ar ages in Alaska (Newberry et al., 1998). The plutons associated with known gold deposits generally exhibit Rb-Y-Nb concentrations (Fig. 2) and $^{87}$Sr/$^{86}$Sr isotopic signatures (0.707-0.714) most consistent with arc-generated magmas that have assimilated a crustal component during their ascent (Sinclair, 1995, Newberry et al., 1998, Mortensen et al., 2000, and Newberry, 2000). Subduction of

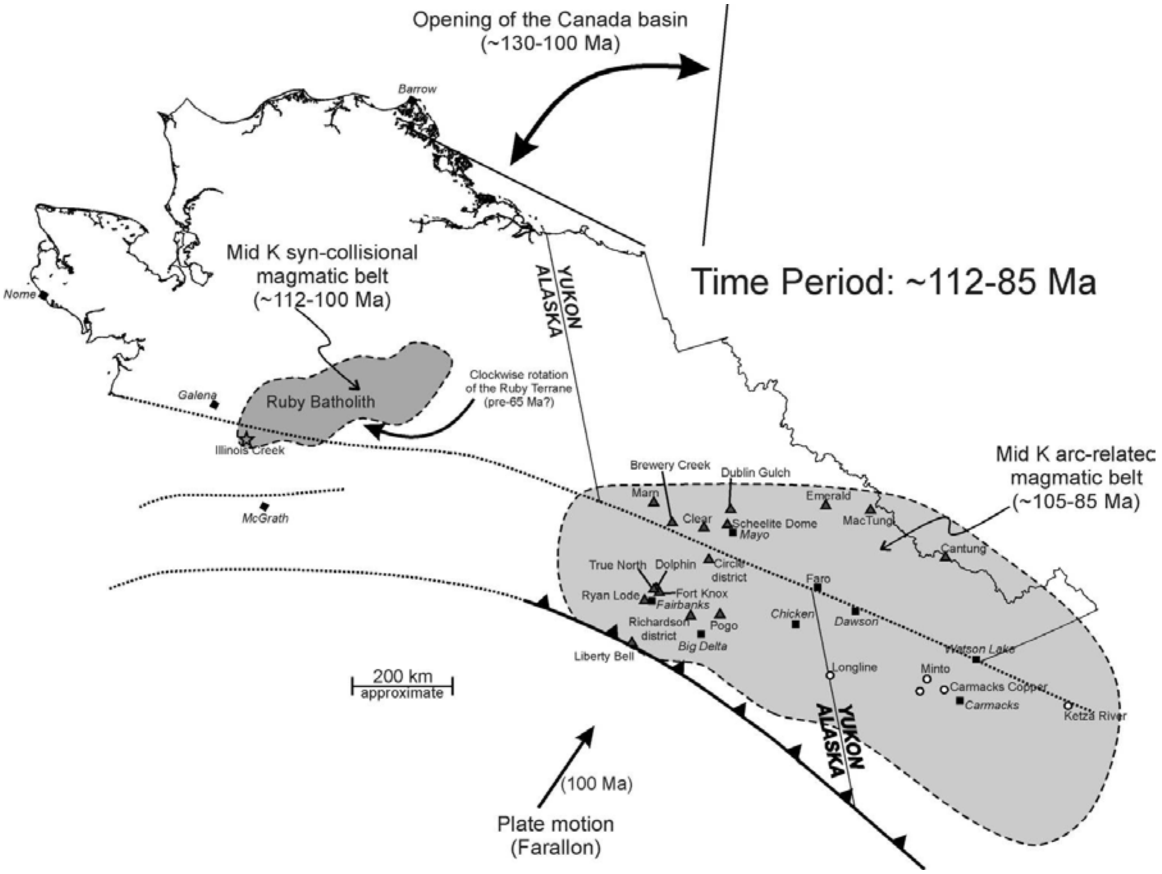

Figure 9: Location of TGP gold occurrences with respect to magmatic belts in their paleo-positions (112-85 Ma). Formation of the Ruby batholith and rotation of the Ruby terrane as a result of the opening of the Canada basin. Tombstone suite magmatism as a result of the subduction of the Farallon plate. Dotted lines represent future approximate major fault locations for reference. Timing and direction of subduction plates and rotation of the Ruby terrane are derived from Plafker and Berg (1994) and Plafker et al. (1994).

the Farallon plate is contemporaneous with these plutons (Plafker and Berg, 1994). 450 km of displacement has occurred along the Tintina fault since early Tertiary time. In Yukon, known Tombstone-Tungsten plutons are dominantly north of the Tintina Fault, whereas in Alaska correlative plutons are south of the Tintina fault. A tectonic reconstruction of the Tombstone-Tungsten suite shows more clearly the spatial relationship of interior Alaska plutonic rocks and their associated deposits with those in Yukon (Fig. 9).

**Late Cretaceous Magmatism:** Late Cretaceous, ~70-65 Ma plutons and intrusive dikes are associated with several gold deposits in Alaska and the Yukon. These gold associated igneous rocks include porphyritic rhyodacite and rhyolite, quartz monzonite, and granite porphyry. In southwest Alaska, concentrations of Rb, Y, and Nb (Fig. 2), major oxide analyses, $^{87}Sr/^{86}Sr$ isotopic ratios (0.704-0.709) from Kuskokwim group plutonic rocks indicate that they are principally I-type metaluminous to slightly peraluminous and probably arc-related (Szumigala, 1993, 1996, Sinclair, 1995 and Newberry et al., 2000). The interpretation of arc related plutonism is consistent with the subduction of the Kula plate as modeled by Plafker and Berg (1994) and Plafker et al. (1994). Age relations of mineralization suggest that coeval igneous bodies and mineral deposits in east central Alaska (Mosquito and the Taurus porphyry, Leriche, 1995), southern Alaska (Golden Zone), and the central Yukon (Casino and Mount Nansen) may be related to the same subduction event associated with the southwestern Kuskokwim group deposits (Donlin Creek, Nixon Fork, Vinasale Mountain, etc., Fig. 10). Tectonic reconstruction of this magmatic suite shows a central area without late Cretaceous deposits. The reason for this blank area may reflect lesser exploration activity due to lack of easy access. However, the potential for this region appears to be high considering this magmatic suite overlaps the Tombstone-Tungsten plutonic suite (Figs. 10, 11 and 12).

**Eocene Volcanics** (~55 Ma)**:** Bimodal Eocene volcanics shown on figure 11 is a small part of this disperse suite apparently related to some Au-Ag epithermal occurrences in Alaska (Ptarmigan Hill) and the Yukon (Grew Creek and Pluto). K-Ar ages of secondary biotite (57±2 Ma) from the Taurus deposit hosted in a ~70 Ma porphyry (Nokleberg et al., 1995) and the nearby 56±2 Ma Push-Bush prospect (Sinclair, 1986) indicate a broad region of thermal resetting and mineralization as a result of the Eocene volcanics. Intrusions of this suite are granite cut by diabase dikes. The bimodal character and trace element signature of this widespread suite indicates a broad, short lived, extensional setting. Although this igneous event is not currently considered as a major gold producer, displacement of the associated ~55 Ma mineral occurrences is believed to mark the earliest onset of major motion along the Tintina and Denali fault systems (Figs. 11 and 12). Other occurrences of this suite are mostly Ag-Sn systems.

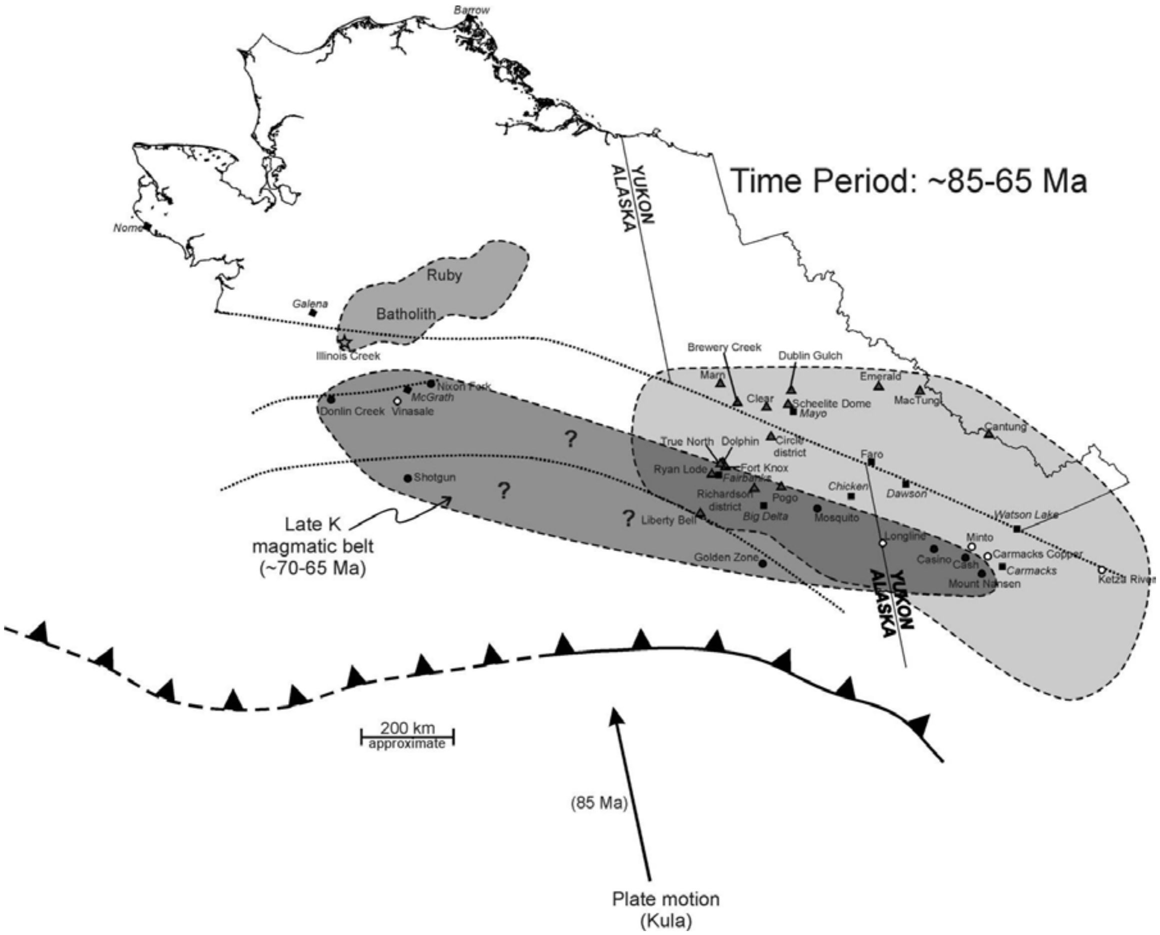

Figure 10: Introduction of Late Cretaceous magmatism and associated deposits due to subduction of the Kula plate. Large scale future faults are shown as thin dashed lines. Shaded regions represent magmatic belts based on deposit and intrusion age dates and may not be all-inclusive. Plate motions and subduction zones are derived from Plafker and Berg (1994) and Plafker et al. (1994).

### Displacement Along Major Faults

The timing and motion along the major faults has been studied previously by several workers. Although there are numerous chronological and geometric discrepancies that have yet to be reconciled, our reconstruction relies primarily on the model provided by Plafker and Berg (1994) and Plafker et al. (1994) to estimate the positions of gold deposits in the TGP (Figs. 9, 10, 11 and 12).

Motion along the Tintina-Kaltag fault system (including the Iditarod fault) is considered to be a dextral displacement of 450 km on the Tintina fault (on the eastern end), and 150 and 90 km on the Kaltag and Iditarod faults, respectively (on the western end). While a 450 km displacement on the eastern side of the Tintina fault system implies the same displacement on the western end, current information does not easily account for 210 km of displacement on the Kaltag side of the system. It has been suggested that the remaining 210 km lies primarily in the hinge splays and crustal shortening where the Tintina and Kaltag faults meet (Dover, 1994, Chapman et al., 1985). Poor exposure and multiple locations of mapped high angle faults make structural interpretation difficult in this region.

Motion along the Denali-Farewell fault system is analogous to the Tintina-Kaltag system. Dextral motion along the Denali fault is approximated at 350 km (to the east) and 140 km on the Farewell fault (to the west). Again there is a discrepancy of 210 km that is accounted for in the hinge splays and crustal shortening where the Denali and Farewell faults meet. Because of these complexities our model is restricted to major movement along faults of reasonable certainty.

The timing of initial movement on these fault systems also is somewhat dubious. The initiation of motion on the Tintina fault is unknown but major displacement is modeled to be post late Cretaceous in age (Plafker and Berg, 1994, Plafker et al., 1994). Displacement of ~55 Ma volcanic-related epithermal Au-Ag systems near Chicken, Alaska (Ptarmigan Hill) and Ross River, Yukon (Grew Creek) indicate that major displacement began no sooner than 55 Ma (Figs. 11 and 12). Age data from mineralized structures (~90 Ma) within the Tombstone Suite intrusions (~90 Ma) in Alaska indicate syn-plutonic faulting (e.g. Fort Knox, Ryan Lode, and Dolphin). These mineralized structures may have formed during strike-slip movement initiated by oblique subduction of the Farallon plate and may mark the early inception of a structural regime that later became the Tintina fault.

The early formation of the Denali fault structure likely began as a trench during the subduction of the Farallon plate (Fig. 9). Timing of initial dextral motion along the Denali fault system has yet to be constrained. Assuming movement along the Tintina fault system is post ~55 Ma, and that southern Alaska closed the trench along the now recognized Denali fault at about 85 Ma, simultaneous dextral movement of the Tintina and Denali

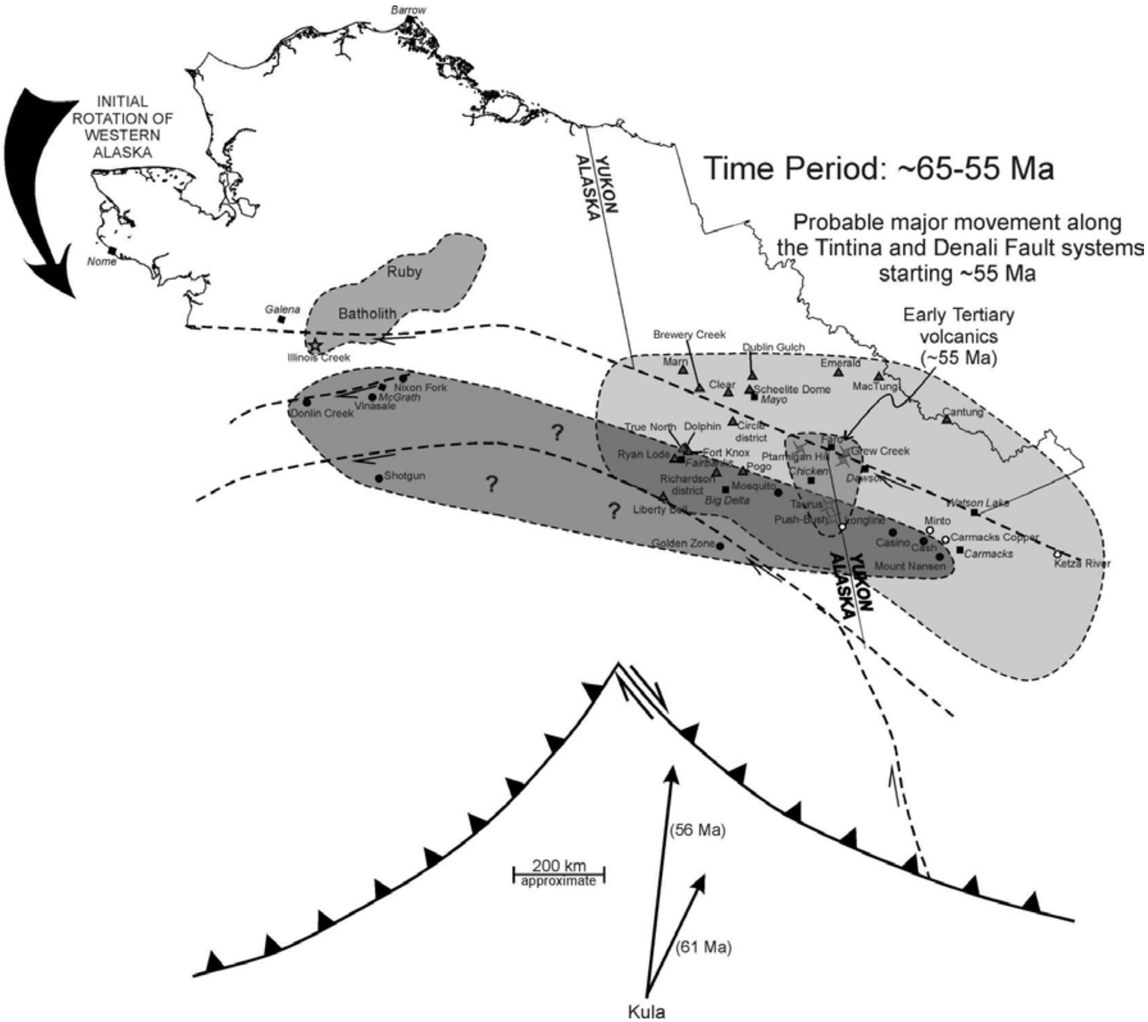

Figure 11: Introduction of Early Tertiary bimodal volcanics. The relatively small region selected relates deposits on either side of the Tintina fault. Note that mid and Late Cretaceous regions overlap north of the Denali fault. Plate motions, subduction zones, and the rotation of western Alaska are derived from Plafker and Berg (1994) and Plafker et al. (1994).

fault systems is likely. It also is reasonable to assume that, as with the Tintina fault, oblique subduction of the Kula plate initiated a strike slip structural regime along the Denali trench that later became the Denali-Farewell fault system.

## Rotation of Western Alaska

Based on geologic and paleomagnetic data, beginning approximately 65-50 Ma western Alaska was rotated about 45 to 60$^o$ to its present position (Plafker and Berg, 1994). This bend is attributed to the convergence of the North American and Eurasian plates (Fig. 11). The axis of the bend is at approximately 147$^o$ longitude (roughly a vertical line though Fairbanks and Anchorage) and corresponds to the hinges in the Tintina-Kaltag and Denali-Farewell fault systems. The presence of the hinge splays and the relatively small amount of movement on the Kaltag and Farewell faults indicate that the Tintina and Denali faults were active during rotation of western Alaska.

## Metal Characteristics and Zoning

Multi-element assay data from drill and rock samples were acquired for systematic evaluation and comparison of various Mid and Late Cretaceous Gold deposits in the TGP. Except for the Dolphin and Cleary Hill, data sets represent ICP multi-element assay data. Bi values for Dolphin and Cleary Hill represent atomic absorption assays. For statistical evaluation, values below the detection limits were assigned a value half of the detection value. Correlation coefficients were calculated from log transformed data to reduce any bias from possible outliers. Average ratios were calculated from raw data. With the exception of the Pogo deposit no cutoffs were invoked and all calculations were performed identically. For the Pogo deposit the data set was trimmed (Smith et al., 1999). Because the Pogo data was treated in a manner inconsistent with the other deposits, it is likely that the overall Bi vs. Au correlation is slightly less and the As vs. Au correlation is slightly more than reported. However, on the basis of the scatter plots for Pogo, conclusions are unaffected. Trend lines through the data points on scatter plots are reduced major axes calculated from log transformed data from the following equation (Davis, 1986):

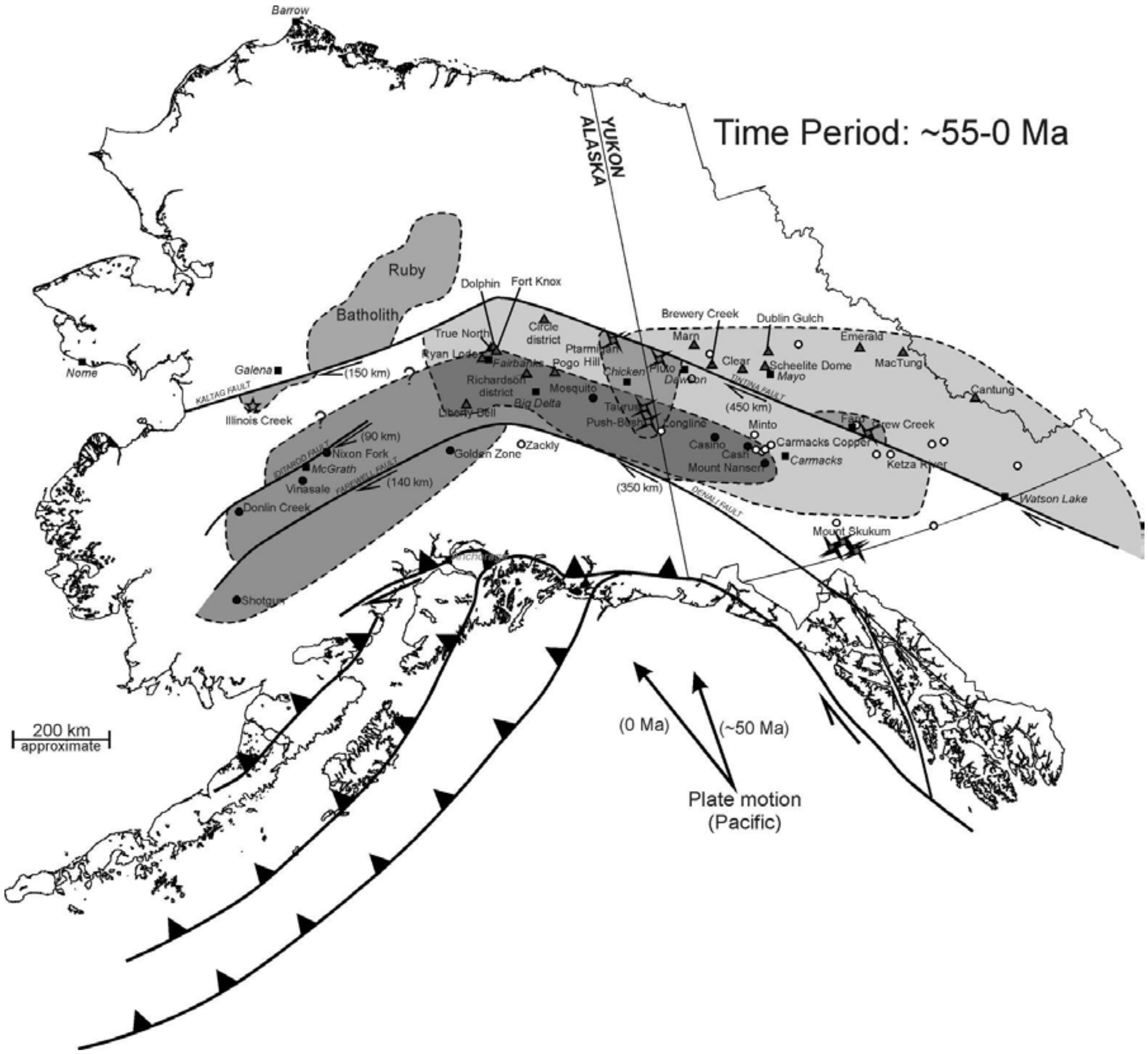

Figure 12: Present day configuration of magmatic belts and deposits. Note that the west end of the Late Cretaceous magmatic belt likely continues to the west but is not shown due to lack of data. Plate motions and subduction zones are derived from Plafker and Berg (1994) and Plafker et al. (1994).

$$y = Y - (\sigma_y/\sigma_x)X$$

Where $Y$ is the mean log Bi value, $X$ is the mean log Au value, $\sigma_y$ is the standard deviation of the log Bi values, and $\sigma_x$ is the standard deviation of the log Au values.

Arc plutonic-related ~90 Ma deposits of interior Alaska (e.g. Pogo, Forth Knox, Dolphin, Ryan Lode, Cleary Hill, True North) represent different deposit emplacement depths due to vertical displacement along high angle northeast trending normal faults (Figs. 3 and 4). These deposits display distinctive relative elemental variations that can be related to depth of host pluton emplacement and distance from a causative pluton (Table 1). Further, deposits in the Yukon Territory believed to be related to the same plutonic suite exhibit identical zoning patterns, and Late Cretaceous (~70 Ma) arc plutonic-related deposits in south and southwest Alaska show an analogous pattern.

For the more proximal and deeper varieties of these deposits, Au concentrations are typically an order of magnitude higher than Te and an order of magnitude lower than Bi. The more distal and shallower deposit varieties contain lower concentrations of Bi and Te with respect to Au. Additionally, in rock samples, Au and Bi are closely linked in intrusion hosted (e.g. Fort Knox) and deeply emplaced plutonic-related deposits (e.g. Pogo) such that Au and Bi show a statistical correlation r > 0.8 (Fig. 5). This close association of Bi and Au almost certainly reflects initial precipitation of the mineral maldonite ($Au_2Bi$), or a similar alloy or alloy melt. Conversely, Au and As show a statistical correlation r > 0.8 for the shallower and/or more distal deposits (e.g. Ryan Lode, Cleary Hill, True North, Fig. 6). The strong correlation of Au and As in shallow/distal environments is likely due to Au inclusions in arsenopyrite and/or as Au in solid solution in arsenopyrite (McCoy et al., 1998). In addition to the systematic variations in Bi vs. Au correlations, best fit trend lines (reduced major axes) through the data clouds decrease in slope in both shallower and more distal environments (Fig. 13).

With the exception of the Shotgun deposit, the Late Cretaceous south and southwest arc-plutonic related deposits behave similarly to the mid Cretaceous deposits in all respects concerning metal variations. Shotgun is the only deposit that does not fall into a consistent order based on Bi vs. Au and As vs. Au correlations (Figs. 7 and 8). This inconsistency at Shotgun is rationalized as multiple fluid pulses redistributing earlier mineralization events and metal

Table 1: Elemental signatures and physical characteristics of selected plutonic-related gold deposits in Alaska and the Yukon Territory. Data sources: 1=McCoy et al., 1997, 2=McCoy et al., 1998, 3=Smith et al., 1999, 4=Metz, 1991, 5=Hulstein and Zuran, 1999, 6=Hart et al., 2000, 7=Cutler, 1994. Elemental data represents rock and drilling samples. *Indicate correlations likely encumbered by the lower detection limit for Bi. Prior to numerical evaluation, values below lower detection were assigned a value half of the detection limit. Correlations were calculated from log-transformed assays. Ratios are averages and were calculated from raw (non-log) values.

**Mid Cretaceous plutonic-related deposits of interior Alaska**

| Deposit | Pressure | Estimated depth | Host Rocks | proximal (p) or distal (d) | Bi vs. Au correlation | As vs. Au correlation | Bi:Au ratio | As:Au ratio | Ag:Au ratio | Pb:Au ratio | Sb:Au ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fort Knox | 1.25 to 1.5 kb[1] | 4 to 5 km[2] | granodiorite/granite | p | 0.88 | 0.23 | 18 | 20 | 0.14 | 15 | 1.8 |
| Pogo | 1.75 to 2 kb[1, 3] | 6 km[2] | gneiss/intrusion | d and p? | 0.89 | 0.29 | 4.2 | 545 | 0.16 | | |
| Dolphin | ~1 kb (?) | 3 km[2] | granodiorite | p | 0.71 | 0.73 | 3.3 | 3140 | 2.0 | 288 | 148 |
| Ryan Lode | 0.5 to 0.75 kb[1] | 2.5 km[2] | granodiorite/schist | p and d | 0.67 | 0.81 | 2.4 | 2899 | 1.3 | 17 | 112 |
| Cleary Hill | 0.9 kb[4] | 3 km[2] | schist | d | 0.64 | 0.82 | 0.75 | 1287 | 0.75 | 86 | 173 |
| True North | ~0.5 kb (?) | 2 km[2] | schist/eclogite contact | d | 0.18* | 0.86 | 0.36 | 1232 | 0.21 | 5.3 | 190 |

**Mid Cretaceous plutonic-related deposits of Yukon Territory, Canada**

| Deposit | Pressure | Estimated depth | Host Rocks | proximal (p) or distal (d) | Bi vs. Au correlation | As vs. Au correlation | Bi:Au ratio | As:Au ratio | Ag:Au ratio | Pb:Au ratio | Sb:Au ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Clear Creek | ? | ? | granitic intrusions/hornfels | p | 0.76 | 0.64 | 31 | 965 | 2.3 | 20 | 4.9 |
| Scheelite Dome | ~2.5 kb[5] | 7.5 km | metasediments/skarn | d | 0.43* | 0.78 | 7.9 | 5072 | | | 97 |
| Brewery Creek | <1 kb (?)[6] | 1 to 2 km[6] | syenite/monzonite sills/siliciclastics | d and p | 0.2* | 0.85 | 1.9 | 1319 | 1.0 | | 1614 |

**Late Cretaceous plutonic-related deposits of south and southwest Alaska**

| Deposit | Pressure | Estimated depth | Host Rocks | proximal (p) or distal (d) | Bi vs. Au correlation | As vs. Au correlation | Bi:Au ratio | As:Au ratio | Ag:Au ratio | Pb:Au ratio | Sb:Au ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nixon Fork | 1 kb[7] | 3 km[2] | skarn | p | 0.87 | 0.24 | 13 | 71 | 0.74 | 2.6 | 20 |
| Shotgun | <1 kb (?) | 1 km[2] | rhyolite-granite porphyry/hornfels | p | 0.45 | 0.26 | 7.1 | 2921 | 5.4 | 12 | 7.8 |
| Golden Zone | <1 kb (?) | 1 km[2] | breccia pipe | p | 0.76 | 0.73 | 6.5 | 1523 | 7.2 | 615 | 40 |
| Donlin Creek | 0.5 kb | 0.5 km[2] | porphyry dikes/siliciclastic sediments | p and d | 0.12 | 0.74 | 4.1 | 1332 | 1.0 | 21 | 48 |

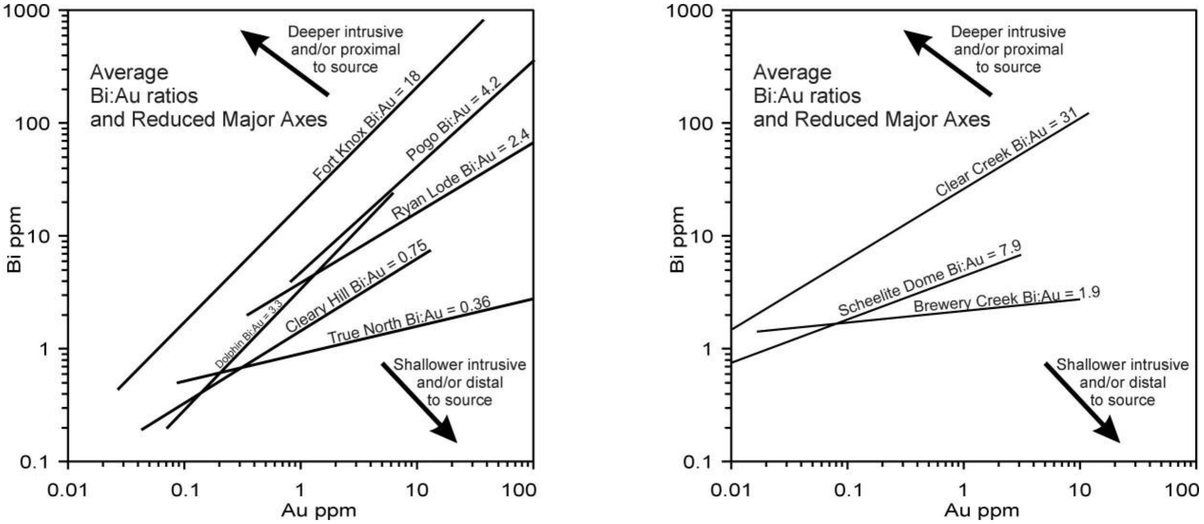

Figure 13: Reduced major axes and average Bi:Au ratios for mid Cretaceous plutonic-related deposits of interior Alaska (left) and Yukon (right). Slopes of the reduced major axes and Bi:Au ratios increase with depth and/or proximity to a causative pluton. Reduced major axes calculated from log-transformed data. Bi:Au ratios calculated from raw (non-log) data.

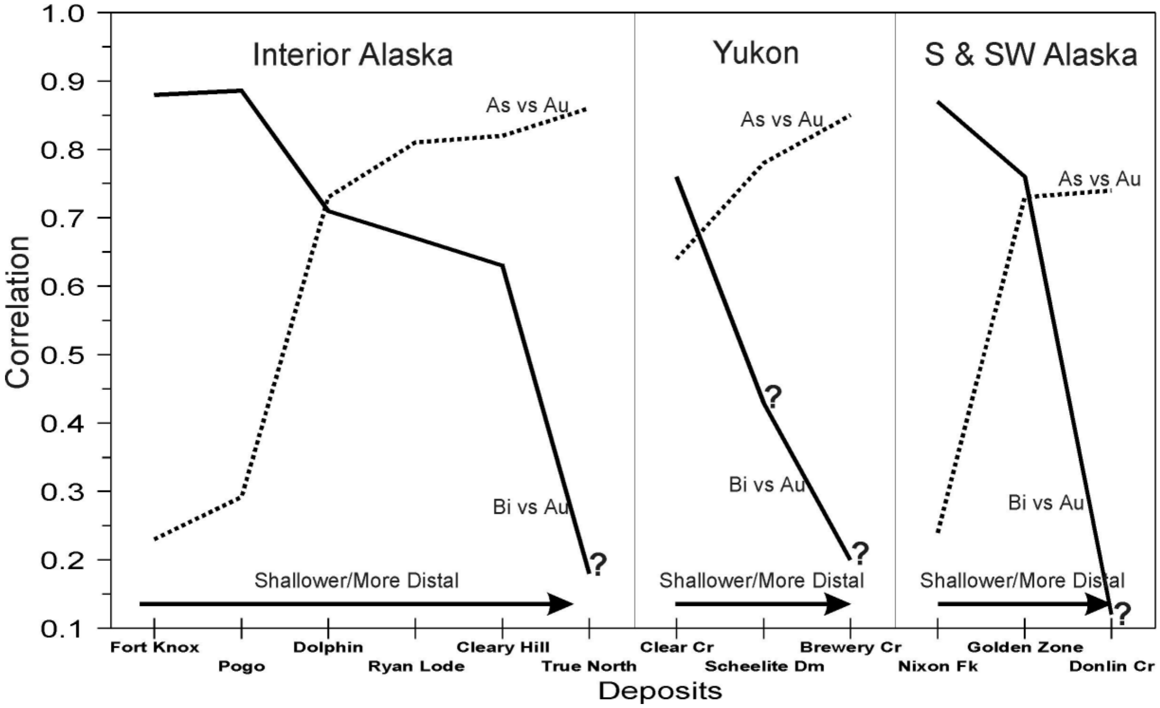

Figure 14: Graph showing systematic variations in Bi vs. Au and As vs. Au correlations with respect to modeled depth of deposit emplacement and/or proximity to a causative pluton. Interior Alaska and Yukon deposits are mid Cretaceous. South and southwest Alaska deposits are late Cretaceous. Question marks denote correlations that are likely encumbered due to lower detection limit truncation. Correlations calculated from log-transformed data.

associations. For the other deposits, the combination of Bi vs. Au and As vs. Au correlation, and Bi vs. Au reduced major axes is very consistent with a deposit's modeled depth of emplacement (from pressure estimates) and proximity to a causative pluton (Figs. 13 and 14). This model could be applied to estimate depths of emplacement for deposits lacking more direct pressure estimates.

Due to lower detection limit truncation most of the Te assays from acquired data sets were not appropriate for statistical analysis. However, data from the Fort Knox, Clear Creek, and Scheelite Dome deposits indicate that there is a moderate to strong correlation between Te and Au in more proximal and/or deeply emplaced plutonic-related deposits. Although there are numerous documented Au-Te minerals in existence, none have ever been observed in arc plutonic-related deposits of the TGP. However, several Bi-Te minerals in close association with Au have been observed petrographically in polished section and by SEM and electron microprobe (McCoy et al., 1998). Thus, the moderate to strong correlation between Au and Te is likely a symptom of Bi-Te minerals occurring in the gold environment rather than a joint occurrence of Te and Au in mineral form.

Several other elements (Ag, Pb, As, and Sb) were examined to determine if any systematic variations could be identified with respect to zoning (Fig. 15). Ag:Au, Pb:Au, and As:Au ratios increase in more shallow emplaced intrusion hosted deposits and decrease distally from

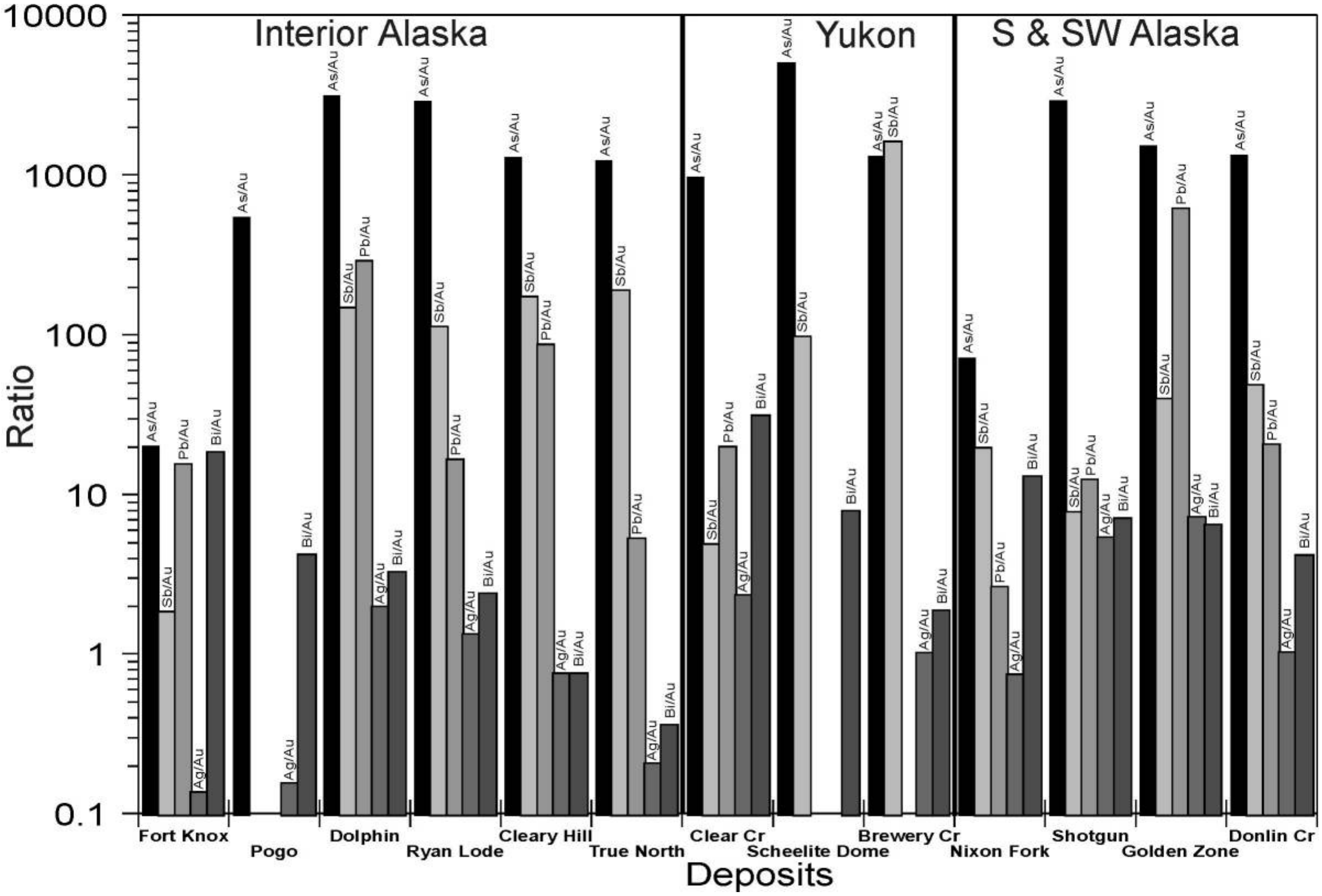

Figure 15: Systematic variations of average metal/gold ratios. Bi:Au ratios increase with depth and/or proximity to a causative pluton. Ag:Au, Pb:Au, and As:Au ratios increase in more shallow emplaced intrusion hosted deposits and decrease distally from causative plutons. Sb:Au ratios increase in both more shallow emplaced intrusion hosted deposits and more distal deposits. Ratios calculated from raw (non-log) data.

causative plutons. Sb:Au ratios increase in both more shallow emplaced intrusion hosted deposits and more distal deposits.

In addition to the metals already mentioned there are various other pathfinder elements associated with these deposits including Zn, Hg, Cu, Mo, W, and Sn. However, due to incomplete data sets obtained for this study, their character with respect to zoning is uncertain.

## Applications in exploration

Variations in Bi vs. Au and As vs. Au correlations and Bi:Au ratios indicate the depth of emplacement and/or proximity to a causative pluton and may be used on a regional scale to target areas for exploration. Higher Bi vs. Au correlations, slopes of reduced major axes and Bi:Au ratios indicate deeper emplacement and/or a proximal fluid source. Higher As vs. Au correlations indicate shallower emplacement and/or distal environments. Further, the Bi:Au ratio varies so systematically with respect to proximity to fluid source that it may be possible to use it on a deposit scale to model the direction and path of fluid transport, and hence, target new areas for drilling. Other metal/gold ratios, although systematic, are more difficult to assess than the Bi:Au ratio. Other ratios are less robust for this use as strong correlations are often lacking and depth of emplacement and proximity to fluid source can exhibit opposing values (i.e. As:Au, Ag:Au, and Pb:Au).

## Limitations

At least three things must be considered to use Bi:Au ratios for modeling a direction toward a fluid source: 1) Detection limits, 2) The Bi vs. Au correlation, and 3) Natural elevated Bi:Au ratios in ~55 to 65 Ma Ag(Sn) lesser gold systems.

Because the correlation is somewhat dependent on the detection limit, detection limits are of primary concern. In the more distal non-intrusion hosted deposits (e.g. Cleary Hill, True North, and Brewery Creek) and some shallow plutonic-hosted deposits (e.g. Dolphin) the concentrations of Bi are often less than the 2 ppm detection limit for standard ICP-ES analysis. Furthermore, for ICP-ES analysis of Bi, the analytical uncertainty is on the order of ±100% up to the 5 ppm level. Thus, areas where substantial proportions of Bi assays are less than 5 ppm, the ICP-ES assay method is inappropriate for assessing Bi concentrations, Bi vs. Au correlations and Bi:Au ratios. To analyze Bi concentrations in such environments an assaying method other than standard ICP should be employed, such as atomic absorption or ICP-MS (mass spec.).

Data sets of appropriate detection limit for Bi and Au may be used for modeling proximity and direction to a fluid source only if Bi and Au are strongly correlative (roughly r ≥0.70). Because greater Bi:Au ratios are found nearer to the fluid source as well as in very distal environments, higher Bi:Au ratios can be misleading. Increasing Bi:Au ratios may be found more distally due to the dissociation of Bi and Au. This dissociation is reflected in decreasing Bi vs. Au correlations; and using Bi:Au ratios as a zoning tool in non-pluton-hosted environments lacking appropriate prior data for correlation analysis is problematic.

Claustice et al. (1999) report significantly higher Bi:Au ratios (≥40:1) associated with ~55-65 Ma Ag(Sn) lesser gold systems in the Chulitna district (Fig. 16). This is distinctly different than the mid to Late Cretaceous plutonic related gold system with Bi:Au ratios ≤ 30:1.

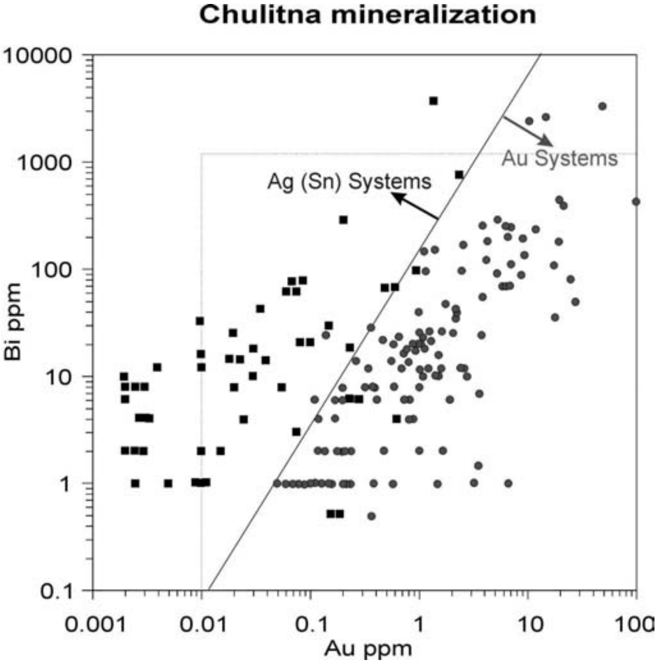

Figure 16: Bi vs. Au plot for the Chulitna district mineralization showing differing regions with respect to Ag (Sn) systems (squares) and Au systems (circles). Data from Clautice et al. (1999).

## Points of interest summary

1) Relative depth of emplacement and proximity to a causative pluton may be approximated by Bi vs. Au and As vs. Au correlations and Bi:Au ratios.
2) In more distal environments it is possible that Bi and Au dissociate which can report misleading high Bi:Au ratios.
3) Bi vs. Au correlations ≥0.70 in non-intrusion hosted environments indicate the data may be appropriate for Bi:Au ratio zoning (by contouring) on the deposit scale.
4) Extremely high Bi:Au ratios (> 40) indicate a ~55 to 60 Ma high Ag(Sn) and lesser Au system is responsible rather than a more desirable mid (~90 Ma) to late (~70Ma) Cretaceous plutonic system.
5) In many cases, standard ICP-ES analysis does not provide lower Bi detection limits appropriate for modeling proximal/distal zoning. The atomic absorption method or ICP-MS is more appropriate.
6) Determination of correlations requires the log-transformation of data to reduce the influence from outliers that may create bogus results.

## Conclusions

Most of the larger gold deposits in the TGP are the result of arc-related magmatism during mid and Late Cretaceous periods. Tectonic reconstructions suggest that mid Cretaceous arc plutonic-related deposits are unlikely to occur south of the paleo-trench marked by the Denali-Farewell fault system. However, Late Cretaceous arc magmatic related deposits are due to a paleo-trench south of the Denali-Farewell fault system and may be found on either side of the Denali fault. Shotgun and Golden Zone are two of the deposits found south of the Denali-Farewell fault system and others are likely to be found in this region in the future. Shaded regions of mid and Late Cretaceous plutonism of figure 12 where pluton density is high, particularly where mid and Late Cretaceous magmatic suites overlap, mark regions of prime gold potential.

Metal zoning for mid and late Cretaceous arc magmatic-related deposits appear to be analogous to one another and are markedly different from Illinois Creek (collisional plutonic-related) and 55 to 65 Ma Ag (Sn) lesser Au systems in the Chulitna district. Where Bi and Au strongly correlate the Bi Au ratio may be used on a deposit scale to model fluid path and direction to source and target areas for drilling.

## Acknowledgements

Several mining companies and individuals contributed data necessary for this study including: Arne Bakke and John Odden/Kinross, John Royall/International Freegold, Lance Miller/Placer Dome, Greg Johnson/Nova Gold, John Mair, Mark Lindsay, and Ben Gage. We would also like to thank several individuals who provided many ideas during informal discussions: Tom Bundtzen, Moira Smith, Cameron Rombach, Dave Adams, Dave Szumigala, Karen Clautice, and Melanie Werdon. Special thanks to Ken Wolf of Avalon Development for providing the initial GIS framework for the tectonic reconstructions. Finally thanks to the reviewers Warren Nokleberg and Elizabeth Zbinden for their suggestions for improvement of the original draft.

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Recommended citation:

Flanigan, Brian, Freeman, Curt, Newberry, Rainer, McCoy, Dan, and Hart, Craig, 2000, Exploration models for mid and Late Cretaceous intrusion-related gold deposits in Alaska and the Yukon Territory, Canada, *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., and Morris, C.L., eds., Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium Proceedings, May 15-18, 2000, p. 591-614.

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