Geology and Origin of Epigenetic Lode Gold Deposits, Tintina Gold Province, Alaska and Yukon

By Richard J. Goldfarb, Erin E. Marsh, Craig J.R. Hart, John L. Mair,
Marti L. Miller, and Craig Johnson

Chapter A of

Recent U.S. Geological Survey Studies in the Tintina Gold Province, Alaska, United States, and Yukon, Canada—Results of a 5-Year Project

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Contents

Figures

Tables

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Abstract

More than 50 million ounces of lode gold resources have been defined in the previous 15 years throughout accreted terranes of interior Alaska and in adjacent continental margin rocks of Yukon. The major deposits in this so-called Tintina Gold Province formed around 105 to 90 million years ago in east-central Alaska and Yukon, and around 70 million years ago in southwestern Alaska, late in the deformational history of their host rocks. All gold deposits studied to date formed from CO_2-rich and ^{18}O-rich crustal fluids, most commonly of low salinity. The older group of ores includes the low-grade intrusion-related gold systems at Fort Knox near Fairbanks and those in Yukon, with fluids exsolved from fractionating melts at depths of 3 to 9 kilometers and forming a zoned sequence of auriferous mineralization styles extending outward to the surrounding metasedimentary country rocks. The causative plutons are products of potassic mafic magmas generated in the subcontinental lithospheric mantle that interacted with overlying lower to middle crust to generate the more felsic ore-related intrusions. In addition, the older ores include spatially associated, high-grade, shear-zone-related orogenic gold deposits formed at the same depths from upward-migrating metamorphic fluids; the Pogo deposit is a relatively deep-seated example of such. The younger gold ores, restricted to southwestern Alaska, formed in unmetamorphosed sedimentary rocks of the Kuskokwim basin within 1 to 2 kilometers of the surface. Most of these deposits formed via fluid exsolution from shallowly emplaced, highly evolved igneous complexes generated mainly as mantle melts. However, the giant Donlin Creek orogenic gold deposit is a product of either metamorphic devolatilization deep in the basin or of a gold-bearing fluid released from a flysch-melt igneous body.

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Introduction

During the previous 5 years, we have carried out geological and geochemical studies of the major lode gold deposits in interior Alaska and adjacent Yukon, Canada. This area, termed the Tintina Gold Province (TGP), is a region of important new mineral discoveries and exploration interest. Our investigations included detailed descriptions of mineralization styles, mineralogical assemblages, geochemical signatures, and geochronological relations. Igneous rocks that are spatially and temporally associated with the deposits were studied in regard to their genesis and possible relation to the gold-bearing hydrothermal systems. Detailed fluid-inclusion and stable-isotope ore-genesis work was carried out to place geochemical constraints on the ore-forming fluids. Local ore-deposit models for the gold deposit types within the TGP were constructed from the data collected during the research program.

Overview and History of the Tintina Gold Province

The TGP is an area of greater than 150,000 square kilometers (km^2) that includes much of interior Alaska and adjacent parts of central Yukon (fig. A1; Goldfarb and others, 2000; Smith, 2000; see figure 1 of Editors' Preface and Overview). In Alaska, this highly mineralized province includes the area between the regional-scale Kaltag-Tintina and Denali-Farewell fault systems. Where the province continues to the east in Yukon, it is located northeast of the Kaltag-Tintina fault system. This vast region is defined by more than 15 individual gold belts and districts, which traditionally were mainly mined for their placer resources. Recently, however, many of these belts and districts have begun to be recognized for their lode gold potential.

This broad and arc-shaped region, which is about 2,000 km in length and continues from Yukon to southwestern Alaska, was first referred to as the Tintina Gold Belt in 1997 by many company geologists. It was mainly a promotional term for a region of highly varied geology, gold deposit types,

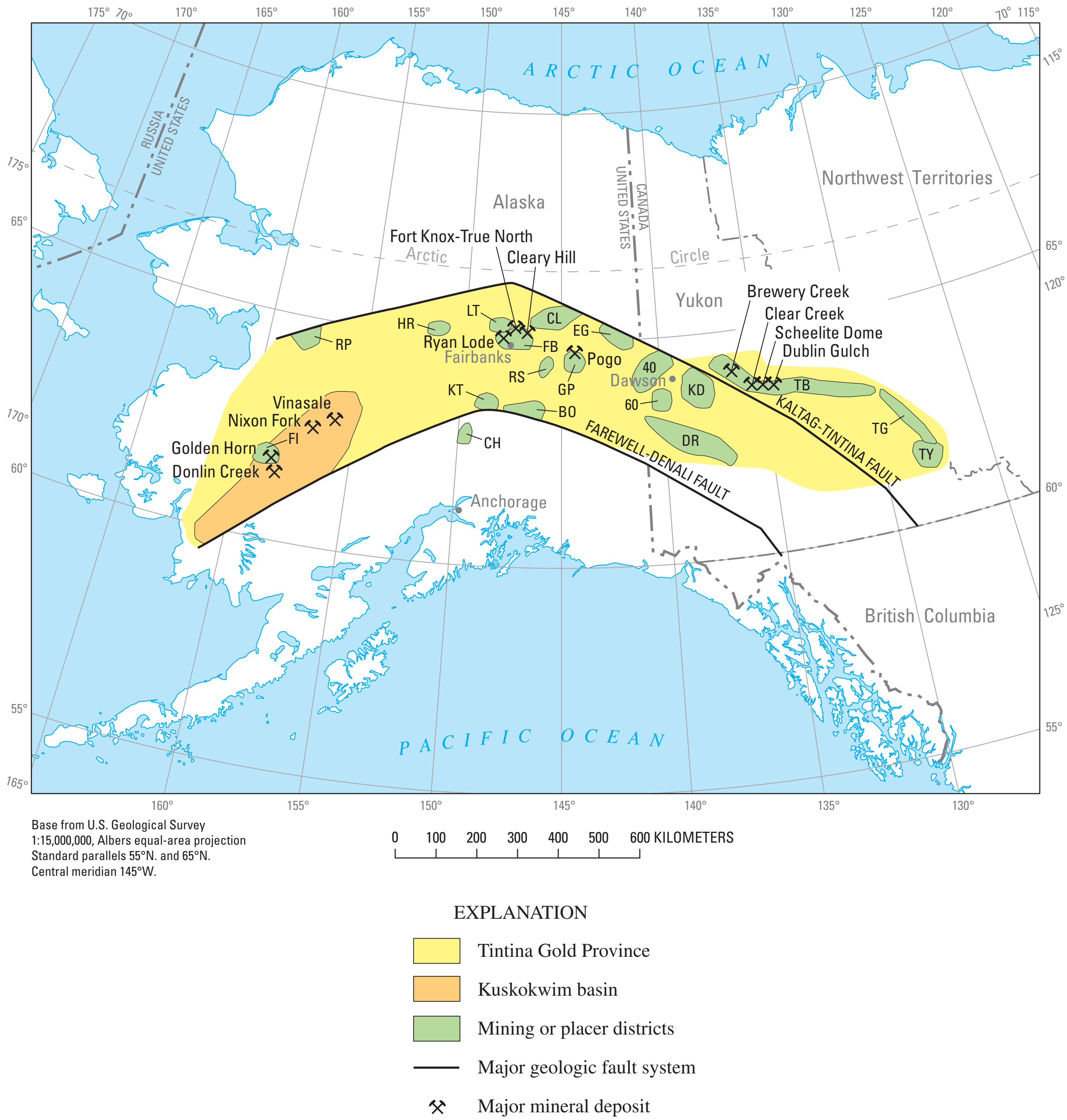

Figure A1. Main gold districts of the Tintina Gold Province of interior Alaska and adjacent Yukon, Canada. The districts are all known for their historic placer gold production, but many areas, notably the Kuskokwim, Fairbanks, Goodpaster, and Tombstone regions, have seen high levels of exploration and concomitant discovery and development during the last 15 years. Mining or placer district names abbreviated as follows: 40, Fortymile; 60, Sixtymile; BO, Bonnifield; CH, Chulitna; CL, Circle; DR, Dawson Range; EG, Eagle; FB, Fairbanks; FI, Flat-Iditarod; GP, Goodpaster; HR, Hot Springs-Rampart; KD, Klondike; KT, Kantishna; LT, Livengood-Tolvana; RP, Ruby-Poorboy; RS, Richardson; TB, Tombstone; TG, Tungsten; TY, Tay River (after Hart and others, 2002).

Figure A2. *A*, Underground development of the high-grade, flat-lying gold orebodies at the Pogo deposit, Goodpaster district, began in 2006. *B*, The first large-scale lode gold development in the Tintina Gold Province was at the Fort Knox deposit near Fairbanks, where low-grade gold ore has been mined since 1996 by open pit methods.

and significant resource potential. Because it was really not a distinct belt and was composed of numerous mineral districts of differing ages and characteristics, Hart and others (2002) argued that it simply be viewed as a large gold province within the northern North American Cordillera and termed the region the TGP. Most significantly, the province includes the Clear Creek, Scheelite Dome, Dublin Gulch, and Brewery Creek deposits of central Yukon; the Fairbanks and Goodpaster gold districts of east-central Alaska; and the lodes of the Kuskokwim basin of southwestern Alaska.

Exploration in the eastern part of the TGP began near the turn of the 20th century. At about the time of the great Klondike (in Yukon) gold rush of 1898, placer gold fields were identified in the eastern part of the TGP, both to the east of the Klondike at Scheelite Dome, Dublin Gulch, and Clear Creek (1894-1901) and to the west in the Fairbanks district of Alaska (1901). Those in the Fairbanks district yielded more than 8 million ounces (Moz) of gold during the 1900s, with other significant (0.5-1.0 Moz of gold each) east-central Alaskan placer districts (fig. A1) including Circle, Fortymile, Eagle, Circle Hot Springs-Rampart and Livengood-Tolvana (Goldfarb and others, 1997). The Yukon placer fields in the TGP were all small; the largest is probably Clear Creek, and it has yielded only 130,000 oz of gold (Allen and others, 1999). Historical lode production had been minor; through the mid-1990s, there was almost no lode gold production from Yukon (Hart and others, 2002) and only a few hundred thousand ounces of gold were mined from a few small, high-grade (10-30 grams per metic ton (g/t) gold) quartz vein systems near Fairbanks (McCoy and others, 1997). However, recent exploration and development of the high-grade Pogo deposit within the Goodpaster district (figs. A1, A2*A*; Smith and others, 1999), located about 150 km southeast of Fairbanks, has led to the start of mining of a 5.6 Moz gold resource late in 2006.

Technological advances during the last decade and favorable existing infrastructure (Mueller and others, 2004) have allowed for the economically successful recovery of large volumes of gold ore for the first time in the eastern Alaska-Yukon region from material with grades of less than 1 g/t of gold (table A1). In 1996, the Fort Knox deposit, located 20 km northeast of Fairbanks, was put into production as a low-grade, bulk-tonnage resource (fig. A2*B*). It has so far yielded more than 4.5 Moz of gold, and has at least 4.6 Moz of gold remaining (Bakke, 1995; Bakke and others, 2000; Kinross Gold Corporation, 2009). During the previous 10 years, the Scheelite Dome, Dublin Gulch, and Clear Creek properties have been continually evaluated for similar bulk-tonnage gold resources. The nearby Brewery Creek deposit was mined for almost 250,000 oz of gold between 1995 and 2002, from shallow oxidized ore zones where refractory gold had been naturally liberated into a form that could be heap leached (Hart and others, 2002).

The first exploration recorded within the western part to the TGP was by Russian prospectors in the Kuskokwim basin in the early 1800s. They discovered the first among many small mercury- and antimony-bearing quartz vein systems that are located throughout southwestern Alaska (Bundtzen and Miller, 1997). Between 1901 and 1916, placer gold accumulations were discovered in many parts of southwestern Alaska, and the resulting districts in the westernmost part of the TGP yielded slightly more than 3 Moz of gold during the subsequent 100 years. A very small amount of gold was recovered from gold-bearing quartz veins at the Golden Horn deposit in the Flat-Iditarod district between 1922 and the mid-1980s (Bull, 1988). U.S. Geological Survey work in the mid-1980s indicated significant gold concentrations in many of the mercury and antimony deposits in the central Kuskokwim basin (Gray and others, 1990), and isotope and fluid-inclusion studies indicated that hydrothermal fluids responsible for

Table A1. Major lode gold resources of the Tintina Gold Province (updated from Hart and others, 2002).

[Abbreviations: Moz, million ounces; g/t, grams per metric ton]

Deposit	Location	Endowment (Moz)	Grade (g/t)	Production to date (Moz)
Donlin Creek	Kuskokwim basin	31.7	2.91	none
Fort Knox	Fairbanks district	9.2	0.93	4.6
Pogo	Goodpaster district	5.6	18.9	1.2
Dublin Gulch	Selwyn basin	1.96	0.916	none
Cleary Hill	Fairbanks district	1.6	34.0	0.5
Shotgun	Kuskokwim basin	1.1	0.93	none
Vinasale	Kuskokwim basin	0.92	2.4	none
Brewery Creek	Selwyn basin	0.85	1.44	0.27
True North	Fairbanks district	0.79	1.69	0.44

formation of these mineral deposits were typical of those that form many lode gold deposits (Goldfarb and others, 1990). Since that work, significant gold resources at historic stibnite prospects have been delineated at Vinasale Mountain and particularly Donlin Creek (table A1), with the latter being one of the world's largest gold deposits known to date.

Geology and Gold Deposits of Central Yukon

The Yukon part of the TGP (fig. A3) is underlain by Neoproterozoic to Early Carboniferous continental margin rocks of the Selwyn basin, a fault-controlled depression developed on the edge of the North American craton. Gold deposits are hosted by phyllite, psammite, calc-phyllite, conglomerate, and marble of the Neoproterozoic to Early Cambrian Hyland Group (Murphy and others, 1993). Middle Jurassic to Early Cretaceous folding, thrusting, and lower greenschist-facies metamorphism of these rocks reflects seaward accretion of terranes along the continental margin. A 750-km-long belt of mainly felsic intrusions, termed the Tombstone-Tungsten belt (TTB), was emplaced into these rocks around 96 to 90 million years ago (Ma) and approximately 8 to 10 million years (m.y.) subsequent to final deformation (Hart, Mair, and others, 2004).

The notably reduced igneous rocks (Thompson and Newberry, 2000; Hart, 2007) of the TTB can be divided into the informally named Mayo, Tungsten, and Tombstone suites (Hart, Mair, and others, 2004). Most of the gold deposits, including those at Scheelite Dome, Clear Creek, and Dublin Gulch, are associated with the subalkaline, metaluminous to slightly peraluminous monzogranites to quartz monzonites, with minor granodiorite, of the Mayo suite. Isotopic data indicate that these rocks of the Mayo suite, as is common in many postcollisional settings, represent a mixture between potassic magmas that were generated in the subcontinental lithospheric mantle (SCLM) and those formed in the overlying lower to middle crust (John L. Mair, Geoinformatics Exploration, Inc., unpub. data, 2008). Emplacement of the more felsic and fractionated, weakly peraluminous, monzogranites and granites of the Tungsten suite, mainly generated from melted continental crust, is associated with formation of world-class tungsten skarn deposits at the easternmost end of the TGP. The least reduced, metaluminous, predominantly syenites of the Tombstone suite, generated from enriched SCLM, are associated with more copper-rich gold occurrences and, in addition, with the gold ores that were mined at Brewery Creek.

The Clear Creek gold deposits consist of auriferous sheeted quartz veins (fig. A4*A*) that cut six stocks of the Mayo suite and, to a lesser degree, are hosted by the surrounding 3- to 5-km-wide zones of hornfels rocks (Marsh and others, 1999, 2003). The veins contain 1 to 2 percent pyrite and arsenopyrite, with lesser pyrrhotite, scheelite, and bismuthinite. The more gold-rich veins may contain greater than 1 percent arsenic, and 100 to 1,000 parts per million (ppm) of both tungsten and bismuth. Gold to silver ratios range from 1:1 to 5:1. Individual veins are generally 0.2 to 5 centimeters (cm) wide and tens of meters long. Vein densities are 3 to 5 veins per meter. Narrow alteration envelopes of quartz, potassium feldspar, and biotite, with some sericite, pyrite, chalcopyrite, hematite, and calcite, surround the quartz veins. Tourmaline and albite are also present in some of the veins. Several small tungsten-tin and tungsten-gold skarns occur where the country rocks are more calcareous. Dates on the stocks by U-Pb techniques are around 91.5 Ma; $^{40}Ar/^{39}Ar$ ages from vein-related micas are around 90 Ma.

The main part of the Dublin Gulch deposit is localized within the apical zone of a granodiorite stock of the Mayo suite (Maloof and others, 2001; Hart and others, 2002). The 600×400-meter (m) area hosts steep, sheeted quartz-feldspar extensional veins (fig. A4*B*), each a few centimeters in width, containing gold, molybdenite, lead-bismuth-antimony sulfo-

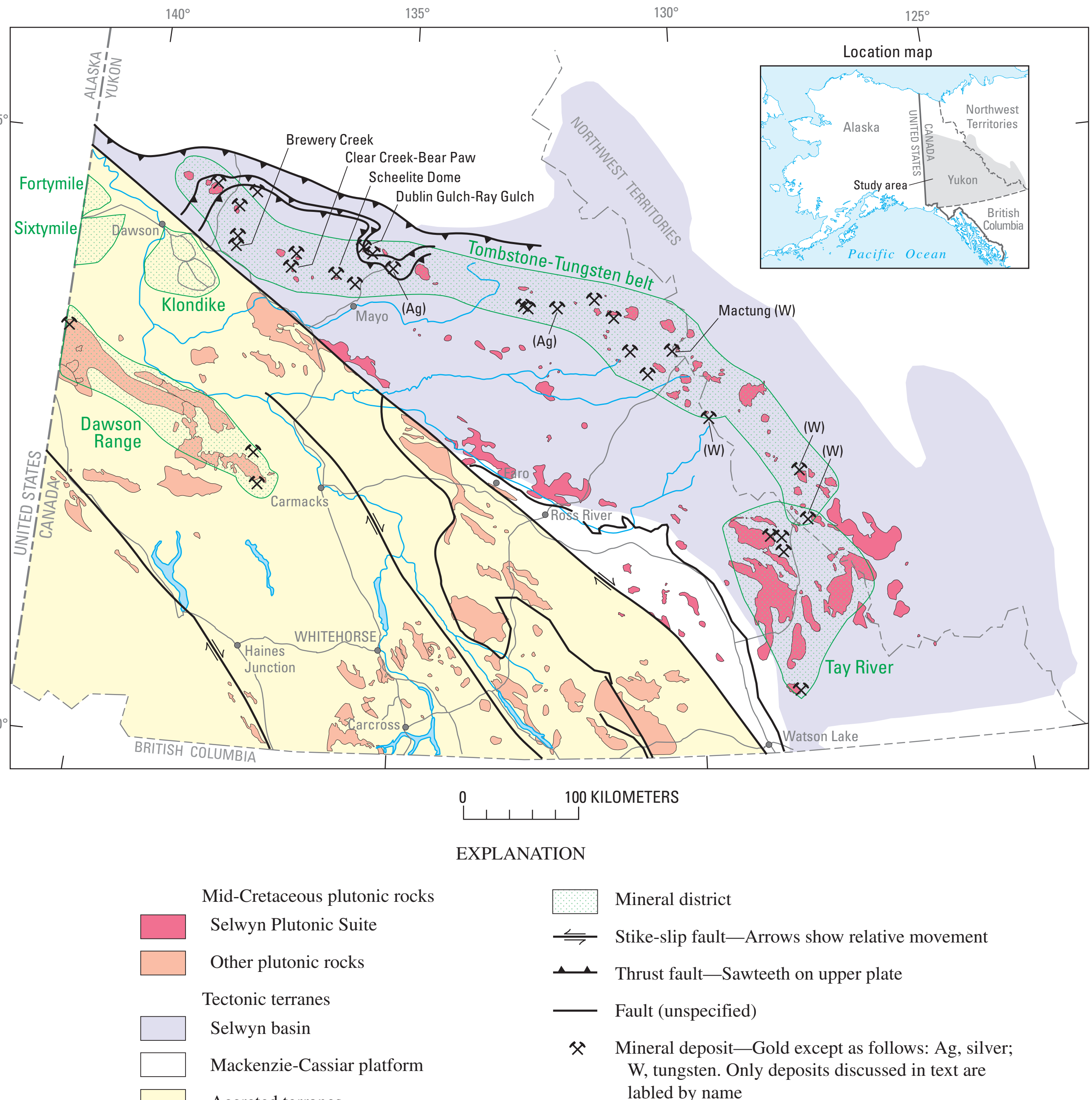

Figure A3. Gold, sliver, and tungsten deposits of the Tombstone-Tungsten magmatic belt in Yukon define the easternmost part of the Tintina Gold Province.

salts, galena, and bismuthinite; alteration phases include albite, potassium feldspar, sericite, carbonate, and chlorite. The deposit is within a few kilometers of the Ray Gulch tungsten skarn deposit, and silver- and lead-bearing veins are in more distal locations. Both pluton emplacement and vein formation are around 94 to 93 Ma (Selby and others, 2003).

In contrast to the other Yukon deposits, the gold occurrences at Scheelite Dome are dominantly hosted by hornfels and are more diverse in style (Mair and others, 2000, 2006). Gold is common in reduced skarns, quartz-feldspar-carbonate veins, and as disseminations in areas of carbonate- and sericite-altered country rocks, mainly in a 10×3-km east-trending zone. The extensional veins are 0.5 to 3 cm wide, and have densities of about 10 veins per meter. In addition to gold, they contain arsenopyrite, pyrite, quartz, albite, ankerite, microcline, muscovite, and tourmaline. Consistent geo-

Figure A4. *A*, Typical gold- and scheelite-bearing, sheeted quartz±feldspar±muscovite veins cutting granite at Dublin Gulch occurrence in Yukon. *B*, Gold-bearing sheeted veins from Dublin Gulch with potassium-feldspar-rich alteration envelope and low-sulfide, quartz-rich infill. *C*, Highly fractured and veined ore from Fort Knox showing dominant "sheeted" veins, and intersecting cross-veins. This is unlike typical stockworks in porphyry deposits. The larger central vein also contains alkalic feldspar. Note the limited alteration selvages adjacent to the veins.

chemical anomalies for bismuth, tellurium, and tungsten also characterize the veins. Alteration selvedges on the walls of the veins include muscovite, carbonate, quartz, and sulfide mineral phases. Locally, gold and scheelite are present in sheeted veins in the monzogranite to quartz monzonite igneous rocks. ^{40}Ar/^{39}Ar dates on gold-related hydrothermal biotite are within 2 m.y. of the 94.59±0.90 Ma U-Pb crystallization age for the igneous rocks. Small silver-, antimony-, lead-, and (or) zinc-bearing quartz vein occurrences surround the Scheelite Dome gold-bearing occurrences.

Geology and Gold Deposits of East-Central Alaska

The east-central Alaskan part of the TGP (fig. A5) is underlain by medium- to high-grade metamorphic rocks, which include those of the widespread Fairbanks-Chena assemblage (Dusel-Bacon and others, 2006). Neoproterozoic to middle Paleozoic protoliths for the metamorphic rocks are mainly clastic sedimentary rocks, with lesser carbonate and magmatic units (Foster and others, 1994). Regional metamorphism likely occurred in the Late Jurassic to Early Cretaceous. The country rocks have been widely intruded by Early Cretaceous felsic to intermediate batholiths, stocks, and dikes. Similar to those of Yukon, these igneous rocks are reduced, have low ferric-to-ferrous ratios (less than 1), and are of low magnetic susceptibility (Hart, Goldfarb and others, 2004). In the Fairbanks area, they occur as shallowly emplaced (less than 3 to 5 km), 94 to 90 Ma isolated domal bodies; in the Goodpaster district, they are more deeply emplaced (5 to 9 km, Dillworth, 2003), widespread 113 to 102 Ma batholiths and 99 to 95 Ma smaller bodies (Day and others, 2007).

In the Fairbanks district, the Fort Knox deposit is located in the apex of a variably porphyritic, monzogranite to granodiorite stock (fig. A2*B*; Bakke, 1995). The gold occurs in steeply dipping, commonly sheeted, quartz-potassium-feldspar veins and in planar quartz veins that occur along later gently to moderately dipping shear zones cutting the igneous rocks (fig. A4*C*). High fineness gold in the veins is commonly intergrown with native bismuth, bismuthinite, and tellurobismuth (McCoy and others, 1997). Total sulfide volumes are much less than 1 percent and include phases such as pyrite, pyrrhotite, arsenopyrite, scheelite, and molybdenite. Alteration phases include potassium feldspar, albite, biotite, sericite, and ankerite. An Re-Os date on hydrothermal molybdenite of 92.4±1.2 Ma is identical to the crystallization age of the Fort Knox stock (Selby and others, 2002). Isotopic data from the ore-hosting stock at Fort Knox indicate an origin similar to Cenomanian magmas in Yukon, reflecting both mantle and crustal contributions (Haynes and others, 2005).

Numerous smaller gold deposits are also spread throughout the Fairbanks district (fig. A6; Goldfarb and others, 1997; McCoy and others, 1997; Bakke and others, 2000; Hart and others, 2002). The True North deposit (figs. A5, A6), originally prospected 100 years earlier as an antimony prospect, was mined for gold at a small scale, providing additional feed for the Fort Knox mill, from 2001 to 2005. This deposit, located about 20 km northwest of Fort Knox, comprises gold in quartz veinlets, disseminations, and breccia along a shallow thrust in carbonaceous felsic schist. The fine-grained gold is associated with pyrite, arsenopyrite, and stibnite. Igne-

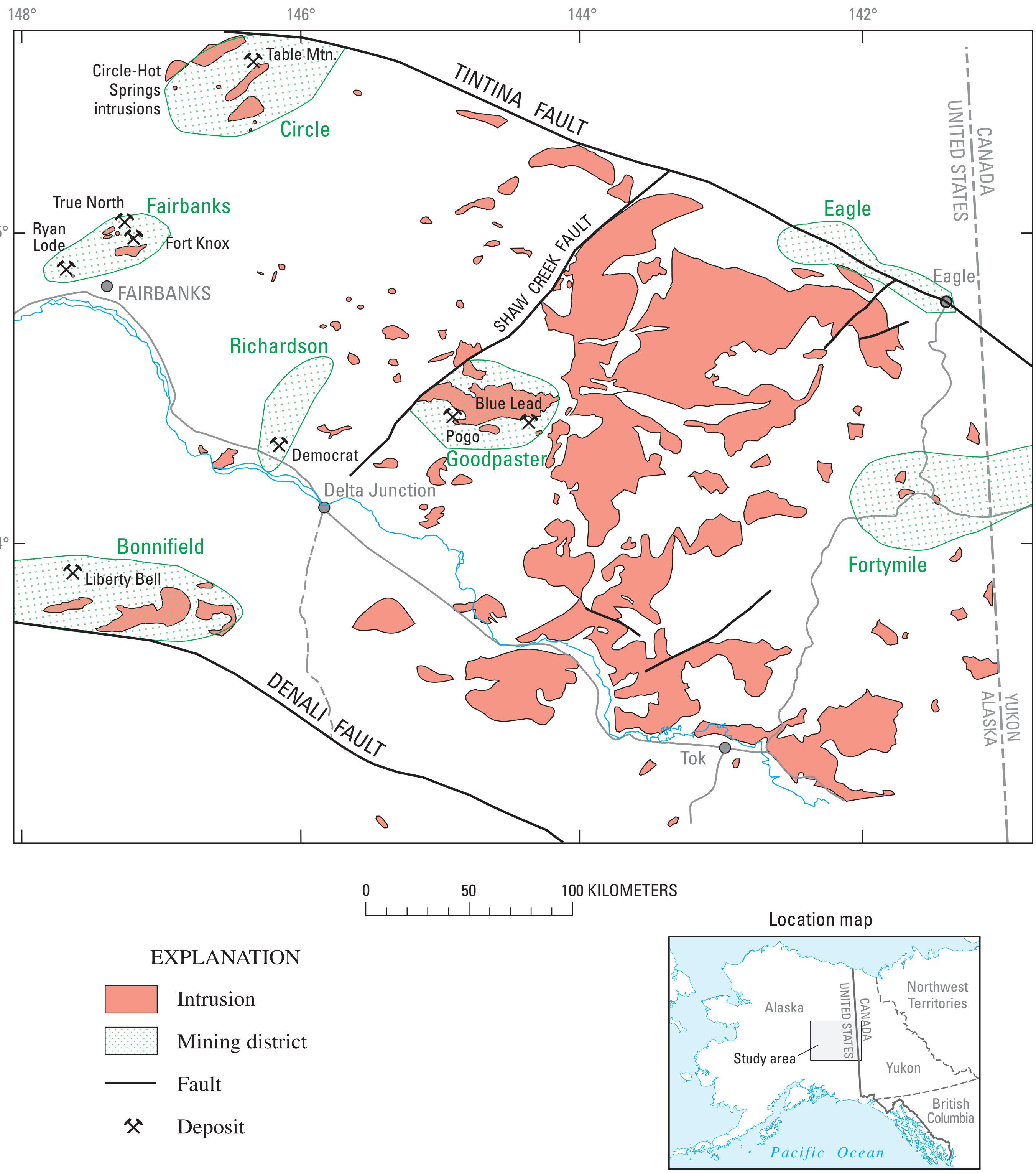

Figure A5. Gold districts (pattern) of the Tintina Gold Province in east-central Alaska and spatially associated reduced mid-Cretaceous igneous rocks (shaded) (from Hart and others 2002).

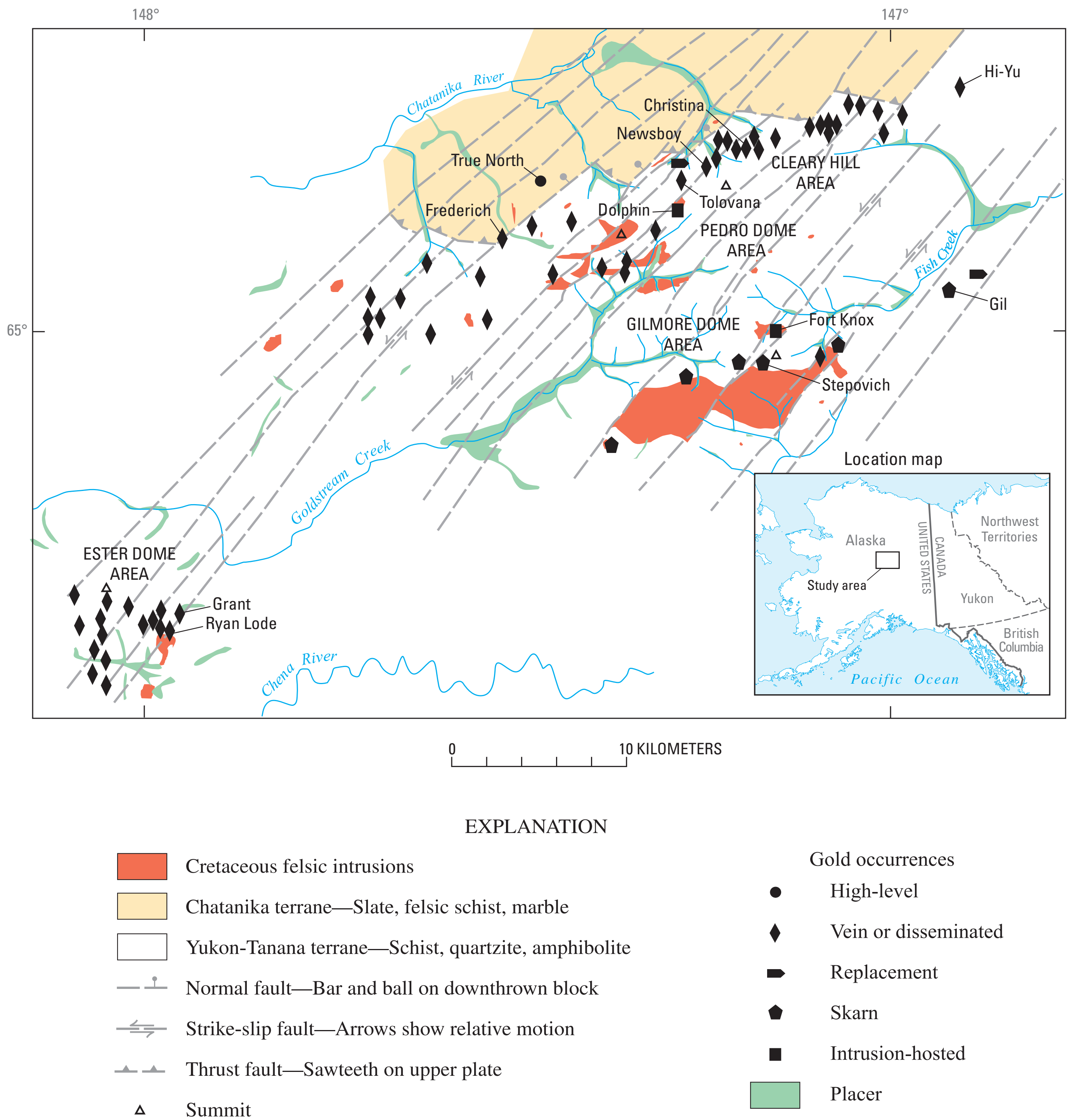

Figure A6. Gold deposits of the Fairbanks district (from Hart and others, 2002).

ous rocks are not recognized at the deposit. The Gil deposit, about 10 km east of Fort Knox, is a sheeted gold-bearing vein system in calc-silicates that likely formed above an as-yet-unroofed pluton intruding schist; other small and subeconomic tungsten skarns also occur in the same area. Many shear-hosted gold-bearing quartz veins, typically dominated by arsenopyrite, occur throughout the district (fig. A7). The largest, the Ryan Lode, occurs along the sheared margin of a tonalite stock. The majority of the schist-hosted deposits (for example, Grant, Cleary Hill, Newsboy, Hi-Yu, Christina, Tolovana) are along steeply dipping, northeast- or northwest-trending fault zones and have characteristic quartz-sericite-ankerite alteration haloes. $^{40}Ar/^{39}Ar$ dates on micas of 89 to 88 Ma for Ryan Lode (McCoy and others, 1997) and 103 Ma for Hi-Yu (R.J. Goldfarb, unpub. data, 2007), as well as a preliminary Re-Os sulfide date of 92 Ma for Tolovana (R.J.

Figure A7. Small shear-hosted gold vein system at the Tolovana deposit, Fairbanks district.

Goldfarb, unpub. data, 2007), suggest that the schist-hosted deposits both overlap and predate Cretaceous magmatism in the district.

High-grade, low-angle, multiphase, shear-hosted veins (fig. A2*A*) cutting mainly gneiss units (Day and others, 2003) and averaging 7 m in thickness with an areal extent of as much as 1.4×0.7-km (Smith and others, 1999; Rhys and others, 2003) were discovered at Pogo in 1996. Sulfide phases, comprising about 3 percent of the veins, include arsenopyrite, pyrite, pyrrhotite, loellingite, chalcopyrite, molybdenite, and bismuth- and tellurium-bearing phases. Alteration phases include biotite, quartz, sericite, potassium feldspar, ferroan dolomite, and chlorite. Reduced granites and tonalities of the Goodpaster batholith, located a few kilometers north of Pogo and comprising mainly crustal melts (in contrast to those at Fort Knox and in Yukon), were intruded around 109 to 103 Ma, during the final stages of regional metamorphism and deformation (Dilworth and others, 2007). Igneous activity thus overlaps with the 104.2 Ma mineralization age as determined by Re-Os analysis of ore-related molybdenite (Selby and others, 2002). Other small gold prospects in the Goodpaster area (Shawnee Peak, Prospect 4021), however, have Re-Os ages of around 95 Ma (Hart and others, 2002).

Geology and Gold Deposits of Southwestern Alaska

The far western end of the TGP (fig. A8) is underlain by Late Cretaceous clastic rocks of the Kuskokwim Group (Decker and others, 1994; Miller and others, 2002). These approximately 95 to 77 Ma sandstones and shales filled a northeast-trending, strike-slip basin between a series of older amalgamated terranes. Regional deformation was initiated in the Late Cretaceous and exposed rocks show evidence of only the lowest grades of regional metamorphism. Widespread, mainly intermediate, calc-alkaline volcanic-plutonic complexes formed throughout the region between 76 and 63 Ma. These metaluminous igneous rocks are a part of a very broad (550 km long), subduction-related arc formed from crustally contaminated mantle melts (Moll-Stalcup, 1994). A second set of intrusive rocks is manifest by approximately 75 to 65 Ma felsic to intermediate, peraluminous, hypabyssal granite porphyry dikes and plugs that are most likely melted Kuskokwim Group rocks (Miller and Bundtzen, 1994). Both intrusive suites are spatially associated with gold resources (Bundtzen and Miller, 1997; Miller and others, 2007).

The giant Donlin Creek gold deposit (fig. A9) occurs as a series of prospects localized within an 8×3-km swarm of the hypabyssal granite porphyry dikes (Goldfarb and others, 2004). Thin quartz veinlets, with lesser dolomite and ankerite, fill brittle extensional fractures within the igneous rocks. Fine-grained pyrite, arsenopyrite, and stibnite comprise 3 to 5 percent of the mineralized rock; orpiment, realgar, cinnabar, native arsenic, and graphite are also present. Gold is almost exclusively a refractory phase in the arsenopyrite. In contrast to many of the gold resources elsewhere in the TGP, bismuth, tellurium, and tungsten do not occur in anomalously high concentrations in the Donlin Creek orebody. Sericitization, carbonatization, and sulfidation are common in the veinlet wallrocks. $^{40}Ar/^{39}Ar$ dating of hydrothermal micas suggests veining occurred within a few million years after intrusion of the 75 to 69 Ma dike host rocks. Isotopic data indicate the source magma for the dikes was mainly of crustal origin, probably sediments of the lower parts of the Kuskokwim basin that were subjected to a localized domain of elevated crustal heat flow. A few other gold occurrences in this part of the TGP, including that at Vinasale Mountain, appear to be localized in similar peraluminous dike systems.

A series of gold occurrences in the Shotgun Hills are associated with weakly metaluminous to strongly peraluminous granite to granodiorite stocks and dikes, some of which are porphyritic and locally fractionated to quartz-feldspar porphyry dikes. The Shotgun gold deposit is situated near the apex of one such evolved quartz-feldspar porphyry phase. It occurs as 0.5- to 5-cm-wide stockworks of auriferous quartz

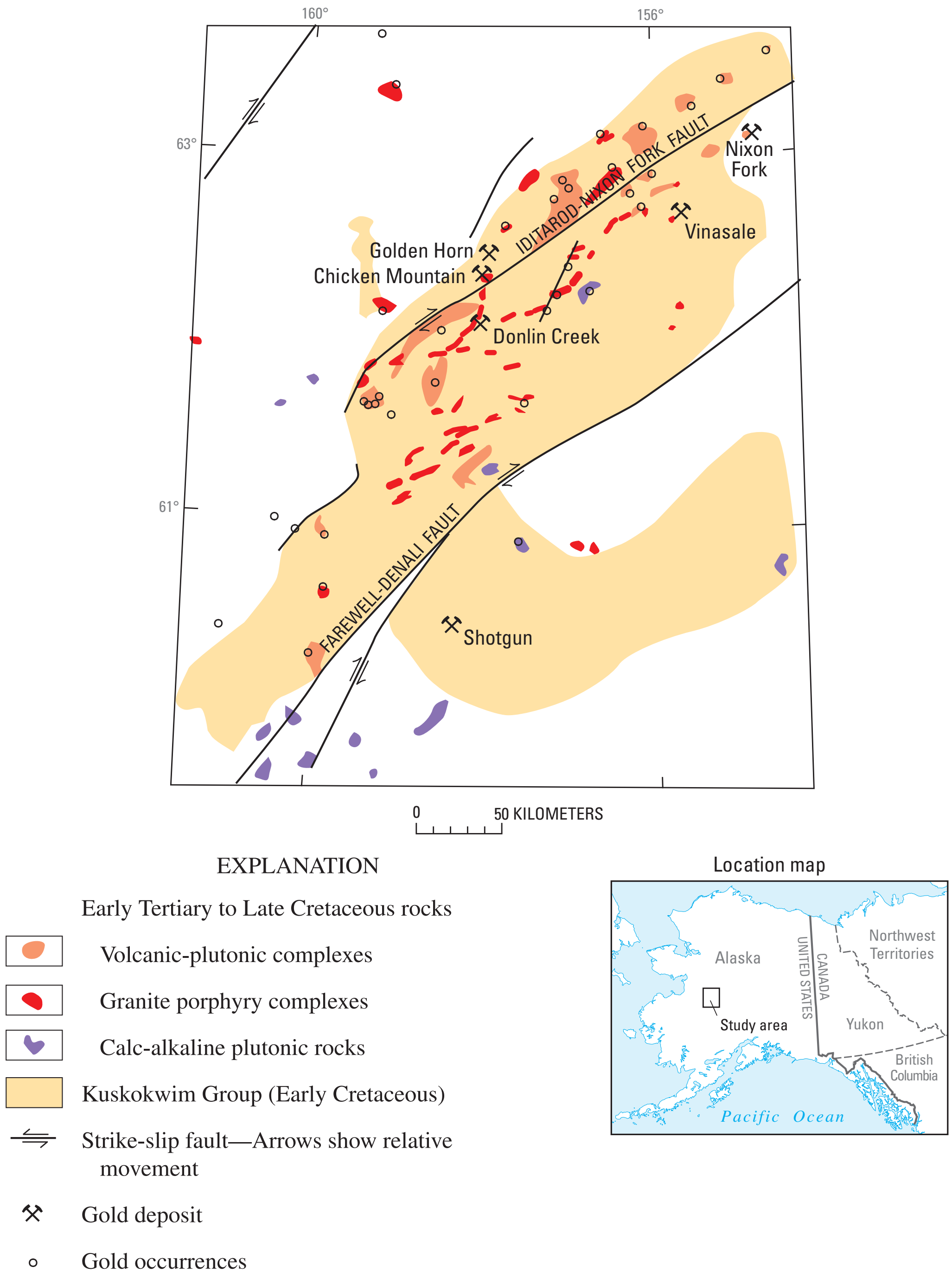

Figure A8. Main lode gold resources in the western end of the Tintina Gold Province (after Bundtzen and Miller, 1997; Hart and others, 2002).

veinlets (Rombach and Newberry, 2001). The veinlets contain less than 1 percent sulfides that are dominated by gold-bearing arsenopyrite commonly associated with pyrite, pyrrhotite, and chalcopyrite, and also loellingite and bismuth-, tellurium-, and tungsten-rich mineral phases. Gold grades tend to correlate with abundance of albite alteration. Tourmaline and quartz commonly cement brecciated porphyry and hornfels rocks. The igneous host rock is dated as 69±1 Ma (Rombach and Newberry, 2001). Isotopic data indicate that this igneous rock has a source in common with those of the other volcanic-plutonic complexes throughout the Kuskokwim region, which is most likely evolved mafic to intermediate mantle melts (J.L. Mair, unpub. data, 2007).

In addition to the Shotgun Hills, important gold resources are associated with other relatively evolved, metaluminous intrusive phases of the volcanic-plutonic complexes that are scattered elsewhere in this part of the TGP. These include auriferous quartz stockworks in monzonite at the Golden Horn deposit in Flat (Bull, 1988) and auriferous skarns at Nixon Fork (Newberry and others, 1997). Where the igneous rocks in these complexes are the most evolved (syenitic to monzonitic), silver-, bismuth-, and tin-rich veins appear to be more dominant than gold-bearing veins.

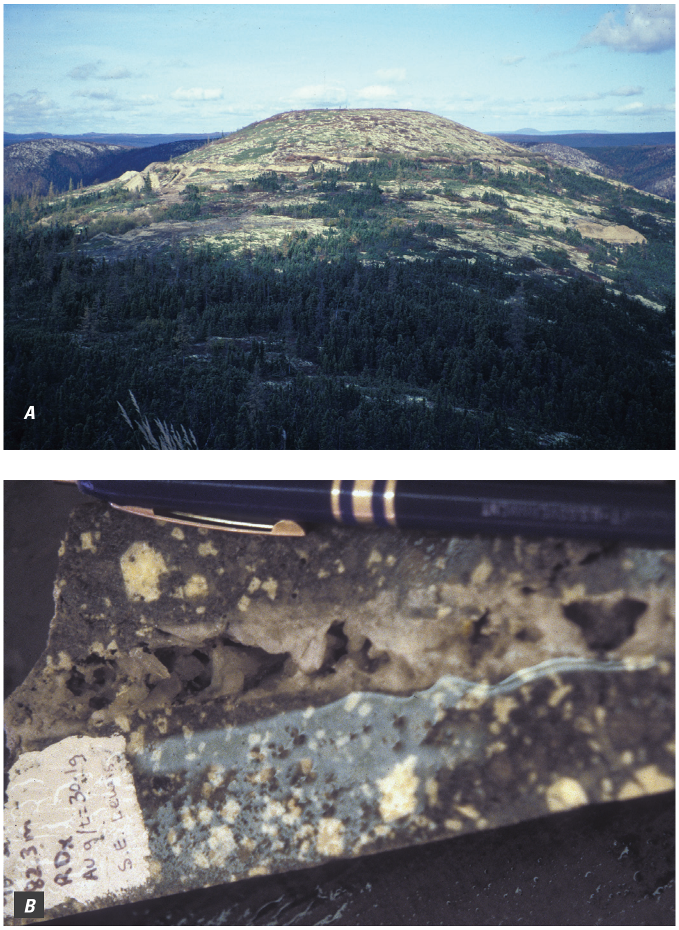

Figure A9. *A*, Aerial photograph of the Donlin Creek deposit area that is centered on a seriees of topographic domes in the Kuskokwim Mountains region of southwestern Alaska. *B*, Most of the mineralization at the Donlin Creek gold deposit occurs in these narrow, vuggy quartz-carbonate veinlets within an igneous dike-sill complex. The igneous host rocks are mainly rhyodacitic in composition, and sometimes porphyritic, as shown here.

Geochemical Constraints on Gold Ore-Forming Fluids

Fluid-Inclusion Studies

Fluid-inclusion microthermometric studies of ore-bearing quartz have allowed for definition of the pressure, temperature, and chemical composition of the ore-forming solutions responsible for the main gold resources in the TGP (table A2). Those gold deposits hosted by and within the surrounding hornfels of the mid-Cretaceous plutons (Fort Knox, Dublin Gulch, Scheelite Dome, Clear Creek) typically developed from low to moderate salinity (≤12 weight percent NaCl equivalent), gas-rich (typically ≥15-20 mole percent CO_2) fluids at temperatures of 290°C to 380°C, and pressures of 1 to 2 kilobars (kb) (or 3.5 to 7 km depth); the Dublin Gulch veins appear to have been slightly cooler, and the Scheelite Dome veins are likely slightly deeper in origin relative to the others. Available data indicate that other mid-Cretaceous gold deposits hosted by metamorphic rocks in the Fairbanks and Goodpaster districts have the same gas-rich, low to moderate salinity fluid type. Pogo and adjacent prospects in the Goodpaster district show indications of being the most deeply formed and hottest among the TGP gold ore systems. In contrast to the gold deposits in the eastern part of the TGP, the Late Cretaceous Donlin Creek and Shotgun deposits in southwestern Alaska formed within the upper 1 to 2 km of the crust; Shotgun is also characterized by an anomalously high-salinity hydrothermal fluid.

Laser-ablation inductively coupled plasma-mass spectrometry (ICP-MS) microanalysis was applied to fluid inclusions in ore-stage quartz to obtain quantitative estimates of any significant differences in the relative abundances of a variety of trace elements in the hydrothermal solutions of the various gold deposits of the TGP (Marsh and others, 2005). Single fluid inclusions from intrusion-hosted, gold-bearing quartz-feldspar veins at Fort Knox were analyzed simultaneously for many major, minor, and trace element relative concentrations. Element ratio measurements (all to Na) range from 0.01 to 0.06 for arsenic and 0.004 to 0.03 for antimony in Fort Knox intrusion-hosted quartz veins, but one extremely gold-rich quartz-feldspar vein had a ratio as high as 0.37 for arsenic. In addition, whereas most bismuth ratios were less than or equal to 0.01, one inclusion within the quartz-feldspar vein had a ratio of 0.67. Base metal ratios were consistently less than 0.01 for lead, and 0.01 to 0.05 for copper and zinc. Similar values characterized fluid inclusions from sheeted veins within the stocks at Scheelite Dome and Clear Creek, but inclusions from auriferous veins in adjacent hornfels at Scheelite Dome commonly showed arsenic, lead, and antimony ratios of greater than 1. Data from reconnaissance examination of several other significant gold deposits that are not hosted by the reduced approximately 90 Ma stocks were compared and contrasted with those data from the Fort Knox and Yukon deposits. Analysis of a few of the inclusions from the Pogo deposit showed no obvious distinction from those that typified the intrusion-hosted deposits. At Donlin Creek, inclusions from the main gold resource exhibited highly anomalous ratios of 4 to 15 for arsenic and 3 to 5 for iron, and elevated ratios of 0.1 to 0.3 for antimony, whereas those from the subeconomic Dome property at the northern margin of the Donlin Creek mineralized zone were 0.004 to 0.016, 0.026 to 0.079, and 0.001 to 0.003, respectively. It is unclear as to whether the Donlin Creek ore fluids were indeed exceptionally anomalous or if perhaps significant dissolution of abundant fine-grained arsenic- and antimony-bearing sulfide phases within the quartz veinlets occurred.

Noble-Gas Studies

Noble-gas isotopes were determined for samples of quartz vein material from gold deposits of the TGP. Helium-

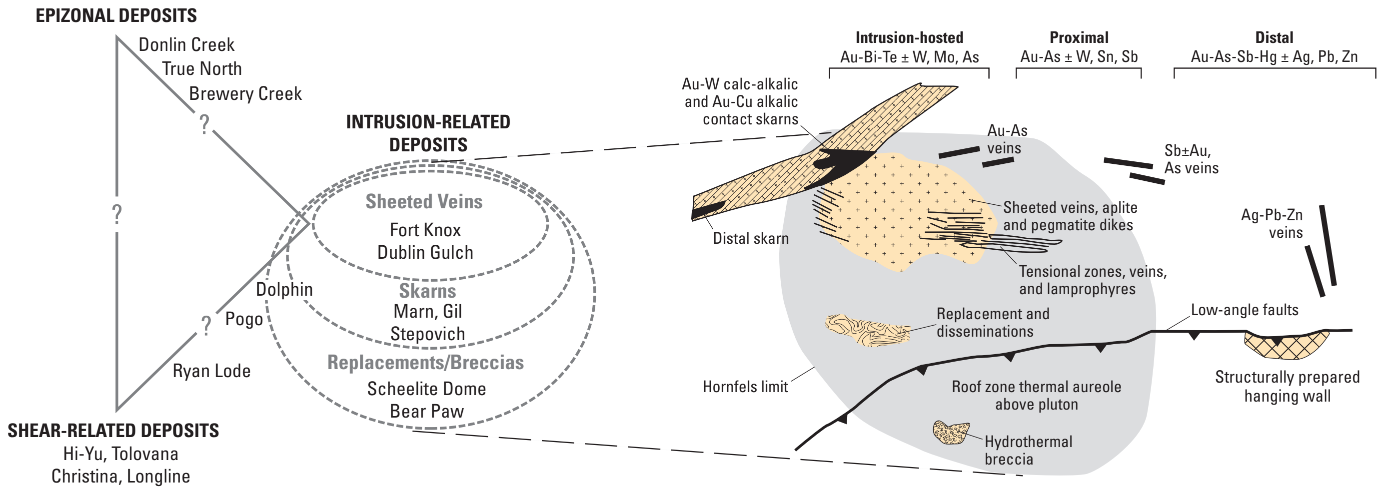

Figure A10. Intrusion-related gold systems in the Tintina Gold Province are characterized by a model that has differing deposit styles, metallogeny, and geochemistry surrounding a causative mid-Cretaceous igneous body. Other shear-related ore deposits, although spatially and temporally associated with mid-Cretecous plutons, are more like classic orogenic gold deposits. Shallowly formed epizonal deposits are more difficult to classify and remain controversial regarding their genesis. (After Hart and others, 2002.)

isotope ratios have *R/Ra* (where *R* is the measured $^3He/^4He$ ratio and *Ra* the atmospheric ratio) values that varied from less than 0.1 for Pogo to greater than 15 for Clear Creek. Preliminary helium data suggest that deposits in Yukon (Clear Creek, Scheelite Dome) have a definite mantle contribution, whereas ore-forming fluids in the TGP deposits sampled in Alaska (Fort Knox, Pogo, Donlin Creek) are dominated by helium with a crustal origin. The $^{40}Ar/^{36}Ar$ ratios from Donlin Creek are close to those for air (295.5) and indicate contamination by air-saturated ground waters in this relatively shallowly formed ore deposit. The other studied gold deposits in east-central Alaska and adjacent Yukon have typical ratios of approximately 500, suggesting a consistent gas source added from the crust or mantle (see Allegre and others, 1987).

Stable-Isotope Studies

Stable-isotope data are consistent with deep crustal sources for major ore-fluid components. Oxygen-isotope data (table A2) for ore-bearing quartz in all gold deposits typically are in the range of 12 to 19 parts per thousand (per mil), indicating a fluid of magmatic or metamorphic source, but with little, if any, contribution from meteoric sources. Nitrogen-isotope data from the Christina deposit in the Fairbanks district suggest that at least the ore fluids for the sedimentary rock-hosted gold-bearing vein deposits in this specific area are of metamorphic origin (Jia and others, 2003). Large variations in sulfur-isotope data (table A2) reflect variable crustal reservoirs for the sulfur that transports the gold ore in the hydrothermal solutions. Extremely negative values for sulfur isotopes for sulfide minerals at Donlin Creek, in the hornfels-hosted veins at Clear Creek, and at Scheelite Dome reflect the highly reduced nature of the sedimentary rocks that provide sulfur to the hydrothermal fluids.

Genesis of Lode Gold Deposits

Geological, geochronological, and geochemical data suggest that both magmatic and metamorphic models can be applied to explaining the distribution of gold resources across the TGP (Goldfarb and others, 2005). Most of the small and widely distributed, approximately 105 to 90 Ma shear zone-related, gold-bearing quartz veins in the Fairbanks (fig. A7) and Goodpaster (fig. A2*A*) districts are best classified as orogenic gold deposits (for example, Groves and others, 1998), which formed during a period of high crustal heat flow and rapid uplift associated with orogenic collapse. Veins show evidence of both brittle and ductile deformation, are most consistently anomalous in arsenic, antimony, and tungsten, and formed from a low-salinity, CO_2-rich ore fluid. The fluid and gold were likely liberated during devolatilization at depth during final stages of deformation and regional metamorphism, and subsequently formed veins at shallower levels in uplifting rocks of the eastern TGP. Pressure fluctuations during hydraulic fracturing and shear movements were the most probable cause for vein formation and gold deposition. Although controversial, many features of the large Pogo deposit also suggest that it is a relatively deeply formed orogenic gold deposit (Goldfarb and others, 2000, 2005).

A second genetic model of intrusion-centered mineralizing systems is most appropriate for other approximately 90 Ma gold resources in the eastern TGP, including the Fort Knox deposit near Fairbanks and those in Yukon (Hart and others, 2002; Hart and Goldfarb, 2005; Hart, 2007). These so-called intrusion-related gold systems (IRGSs) are similar to the orogenic gold deposits in that both deposit types are spatially and temporally associated with igneous rocks, may overlap in tectonic setting, have similar gangue mineralogy, can overlap in trace-element signatures (Ag, Au, As, Bi, Sb,

Table A2. Fluid inclusion and stable isotope geochemistry of ore-bearing samples from deposits in the Tintina Gold Province.

[Abbreviations and symbols are as follows: n.d., no data; °C, degrees Celsius; ≤, less than or equal to; ≥, greater than or equal to]

Deposit	$xCO_2 \pm N_2, CH_4$ (mole percent)	Salinity (weight percent equivalent NaCl)	Immiscible	Pressure (kilobars)	Temperature (°C)	$\delta^{18}O$ quartz (per mil)	$\delta^{34}S$ sulfide (per mil)	Reference
Clear Creek	15	12	Yes	1.4–1.8	300–350	14.0–18.7	-12.7– -9.5, -2.9–+0.4	Marsh and others, 2003
Scheelite Dome	20–60	≤4	No	2–3	290–380	14.1–19.0	-10.9– -7.1	Mair and other, 2006
Dublin Gulch	2–33	1.4–9.8	No	≥1.1	≥150– 271	n.d.	n.d.	Maloof and others, 2001
Fort Knox	22	2–8	Some	1.25–1.5	330–370	12.0–13.5	-3.4	Goldfarb and others, 1997; McCoy and others, 1997; Paul Jensen, Teck-Cominco, unpub. data, 2006
Ryan Lode	12	≤8	Yes	0.5–0.75	270–330	11.7–15.0	0.5–3.7	McCoy and others, 1997
Others—Fairbanks district	1–20	3–5	n.d.	n.d.	275–375	n.d.	0.3–4.1; 8.2–10.9	Metz, 1991; Goldfarb and others, 1997
Pogo	Highly variable	Highly variable	Yes	1.7–2.0	308–570	13.4–15.2	-2.5–+5.5	Smith and others, 1999; Rombach and others, 2002; C. Rombach, unpub. data, 2005
Others—Goodpaster district	Significant amounts	2.5–7.5	Yes	1.4–2.4	225–390	n.d.	n.d.	Dilworth, 2003; R.J. Goldfarb, unpub. data, 2005
Donlin Creek	3–7	3–6	Rare	0.3–0.6	275–300	14.3–24.7	-16– -10	Goldfarb and others, 2004
Shotgun	Variable	Moderate to high	Yes	0.5	280–630	16.4–17.1	-5.9– -5.0	Romach and Newberry, 2001

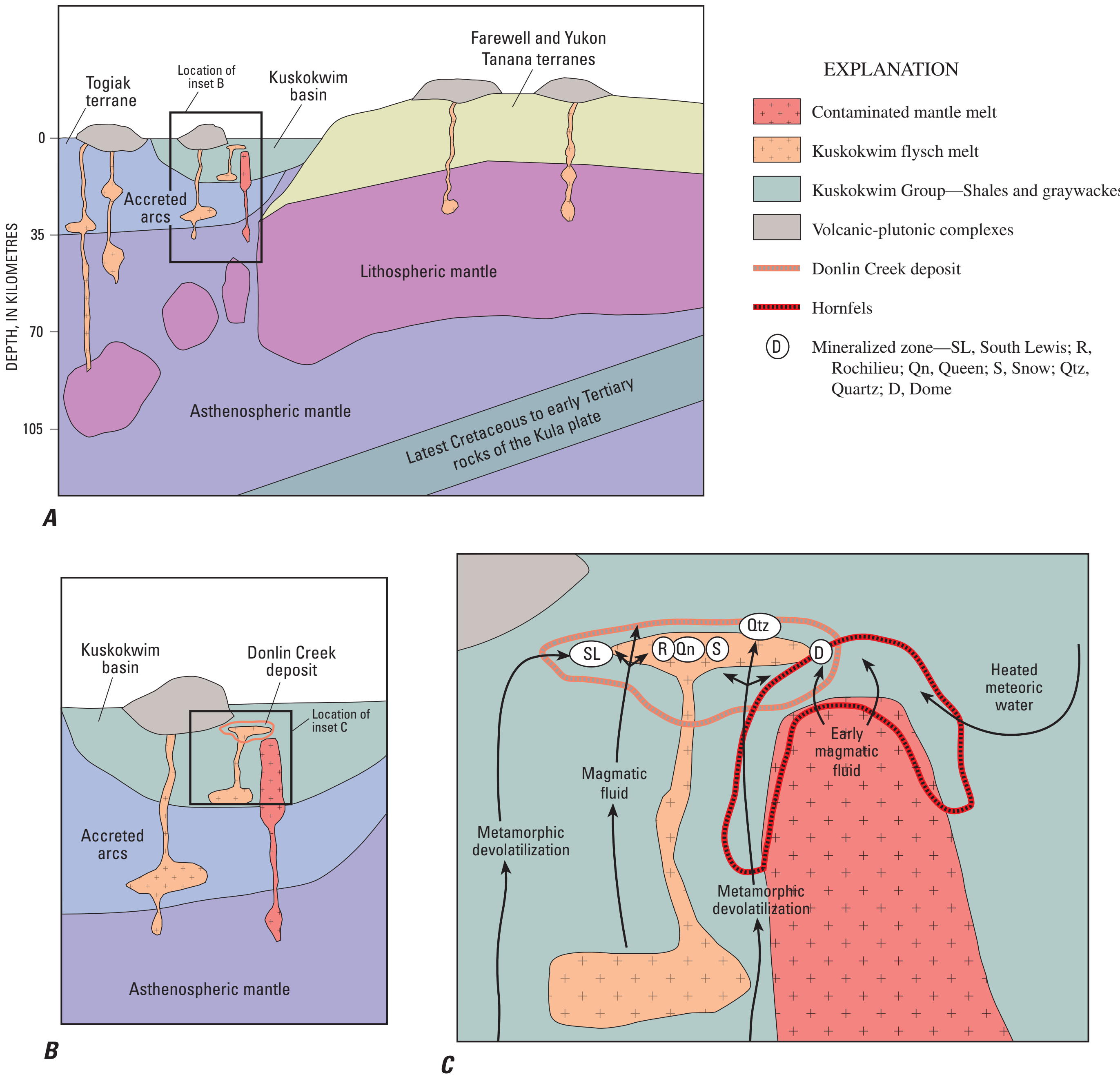

Figure A11. Genetic model for evolution of the Donlin Creek gold deposit. *A*, Small-scale, regional model showing location of inset *B*. Field of view is approximately 480 kilometers. *B*, Inset *B*, showing partial mantle melting above the subducting Kula plate leading to the emplacement of crustally contaminated intrusions and volcanic-plutonic complexes throughout the Kuskokwim basin. In a few locations (including at the site of the Donlin Creek deposit), small, almost pure flysch melts evolved. Shows location of inset *C*. *C*, Inset showing gold-transporting hydrothermal fluids released during devolatilization of flysch adjacent to the larger melts and (or) from the melts themselves. The fluids localized the gold ores in the already crystallized and structurally competent flysch melt dike-sill complex at Donlin Creek. (After Goldfarb and others, 2004.)

Te, and (or) W), and have formed from fluids with very similar chemistries. In fact, the low salinity and high CO_2 content of the IRGSs are very different from most other magmatic gold deposits and has led to much of the controversy regarding identification of IRGSs versus orogenic gold deposits (Groves and others, 2003). A key distinction is that an IRGS represents a zoned system centered around a causative pluton (fig. A10); a complete model would include (1) sheeted gold-bismuth-tellurium-tungsten-bearing quartz veins in the cupola of the intrusion; (2) gold-rich tungsten or copper skarns in any adjacent calcareous rocks; (3) gold-arsenic±antimony tension-vein arrays, disseminations, and breccias within 2- to 3-km-wide hornfels zones; and (4) distal low-temperature silver-lead-zinc veins (Hart and others, 2002). The IRGSs are also significantly lower in grade (less than 1 g/t gold) than orogenic gold deposits (greater than 1-2 g/t gold; commonly greater than 10 g/t gold). The zoned mineralization styles indicate an exsolved magmatic fluid that moved outward from the late-stage crystallizing magma. An abundance of aplites, pegmatites, vein dikes, miarolitic cavities, and unidirectional solidification textures in the igneous rocks is consistent with a fluid-rich melt and thus with a magmatic model. Potassic magmas released from the SCLM could have been the source of the gold that was further concentrated during magmatic evolution in the overlying crust (John L. Mair, Geoinformatics Exploration, Inc., unpub. data, 2008).

Two distinct ore deposit models also characterize the approximately 70 Ma gold deposits in the western TGP (Goldfarb and others, 2004). The gold-forming fluids at the giant Donlin Creek orogenic gold deposit may have been derived by broad-scale metamorphic devolatilization above rising mantle melts that were emplaced into the sediments at the base of the Kuskokwim basin. Alternatively, exsolution of fluids could have taken place from a magma that was dominated by a significant sedimentary rock melt component (fig. A11). Other gold occurrences in the Kuskokwim basin, best broadly classified as simply magmatic gold deposits (for example, Shotgun and Golden Horn), formed via fluid exsolution from fractionation of high-level intrusive systems dominated by a mafic to intermediate composition parent magma of lower crustal or lithospheric mantle origin. These gold deposits seem to be localized at the apices of the more fractionated porphyritic intrusive bodies in the region. The high degree of fractionation is important for preconcentration of metals and volatiles in these gold depositing magmatic-hydrothermal systems.

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