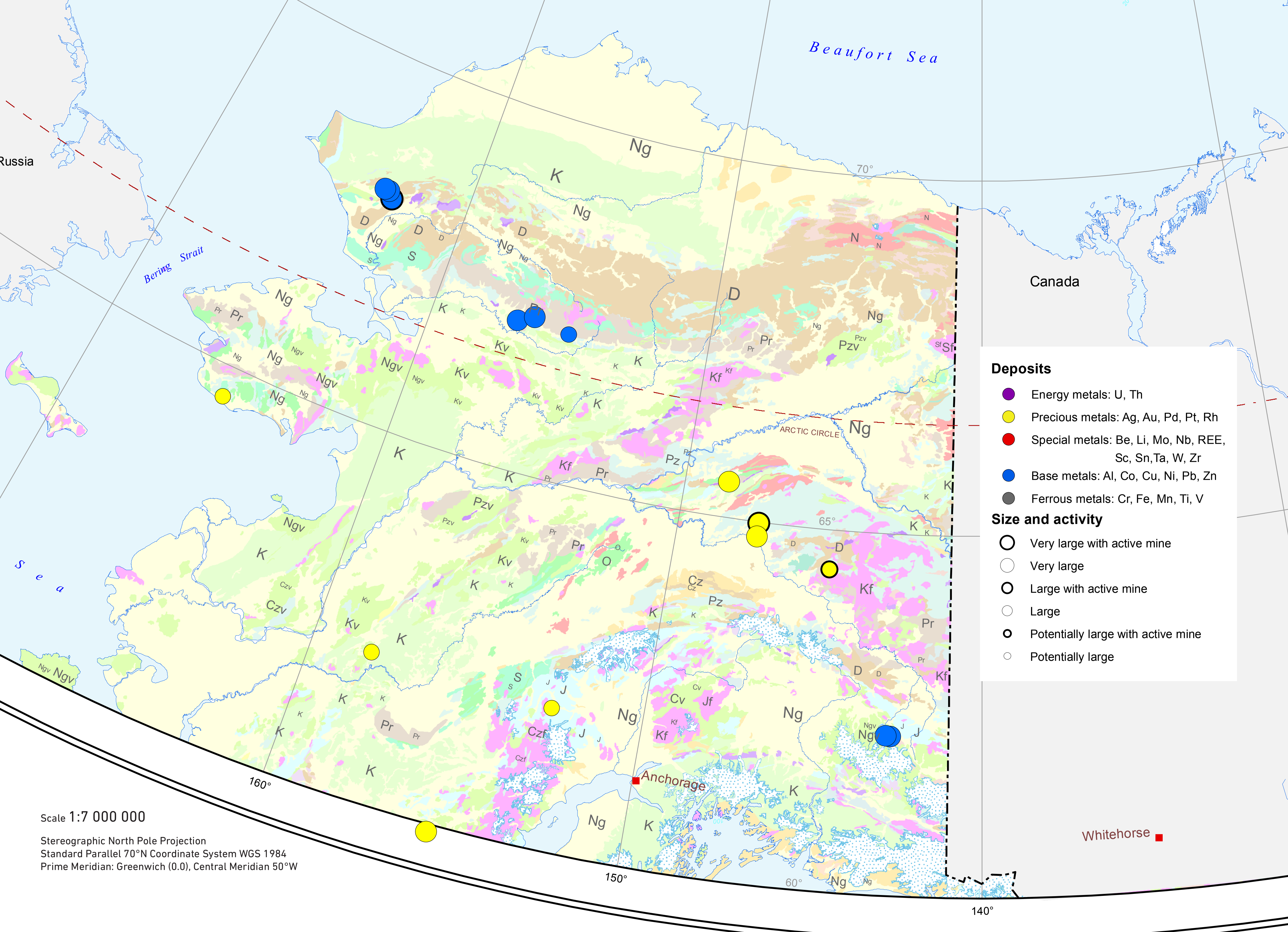
Russia
Bering Strait
Beaufort Sea
Sea
Canada
ARCTIC CIRCLE
Anchorage
Whitehorse
70°
65°
60°
160°
150°
140°
Deposits
Energy metals: U, Th
Precious metals: Ag, Au, Pd, Pt, Rh
Special metals: Be, Li, Mo, Nb, REE, Sc, Sn, Ta, W, Zr
Base metals: Al, Co, Cu, Ni, Pb, Zn
Ferrous metals: Cr, Fe, Mn, Ti, V
Size and activity
Very large with active mine
Very large
Large with active mine
Large
Potentially large with active mine
Potentially large
Scale 1:7 000 000
Stereographic North Pole Projection
Standard Parallel 70°N Coordinate System WGS 1984
Prime Meridian: Greenwich (0.0), Central Meridian 50°W

CHAPTER 1

ALASKA

MINERAL DEPOSITS AND METALLOGENY

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INTRODUCTION

Alaska, the largest State within the United States, and with the majority of Alaska north of latitude 60°, is an important part of the Circum-Arctic region covered by the accompanying metallogenic map. Alaska is a richly endowed region with a long and complex geologic history. The mining history is short by world standards but nevertheless there are a number of world-class deposits in Alaska, of which Red Dog and Pebble are among the largest of their respective types in the world. This chapter provides a brief overview of Alaskan geology, a summary of Alaskan mining history, and a review of the main metallogenic regions of Alaska, with a description of the main deposits within each region. The focus is necessarily on geology and deposits north of latitude 60°N, but for completeness there is a brief summary of geology and major deposits of Alaska to the south of this circum-Arctic boundary. For example, the Pebble deposit is the largest gold resource and one of the largest copper resources in igneous rocks on Earth, but its location at 59° 53' 50" N in southwestern Alaska is slightly south of the 60° N boundary of the enclosed Circum-Arctic metallogenic map. A brief description of Pebble and the similarly more southernly situated orogenic gold and polymetallic volcanogenic massive sulfide (VMS) deposits of the southeastern Alaska panhandle are included here for completeness.

Alaska consists of an amalgamation of terranes that formed at different times in different places and later came together. Thus, this chapter includes both a simplified introduction to Alaskan tectonic history and, for each major region, a summary of the essential geologic features. We provide an overview of the major ore deposit classes and include more detailed descriptions of individual deposits. Owing to space limitations, we have provided fuller explanations for giant deposits (e.g., Red Dog), but less information for the smaller deposits (e.g., those found in the same Brooks Range region of Alaska). Nonetheless, this chapter is intended to provide an overview of Alaskan geology and the important part that it plays in the metallogeny of the Circum-Arctic region. As was the case with some of the now defined large deposits such as at Fort Knox and Donlin Creek, smaller deposits described here could also eventually be sites of future brownfields exploration and identified economic resources.

MAIN GEOLOGIC-TECTONIC FEATURES OF ALASKA (NORTH OF 60°)

Alaska has a geologically complex history that resulted in a collage of terranes or regions having distinct histories, most of which were tectonically assembled from late Paleozoic through Cretaceous (Plafker and Berg, 1994). They now occur as numerous fault-bounded blocks in the northernmost part of the North American Cordillera on the western margin of the Laurentian craton (Colpron et al., 2007). These terranes are comprised of rocks ranging in age from Paleoproterozoic to Recent (enclosed map). The advent of the terrane concept in the 1970s (e.g., Coney et al., 1980) revolutionized the study of geology in Alaska. Initially, many of these terranes were considered exotic (i.e., unrelated to each other and formed in different geologic environments); more recent work has revealed partially common geologic histories and linkages among many of the terranes (e.g., Alexander-Wrangellia-Peninsular composite terrane: Plafker et al., 1994; Beranek et al., 2014; Arctic Alaska, Farewell, and Kilbuck terranes: Bradley et al., 2013). Nonetheless, some of the terranes evolved in widely dispersed locations and were eventually amalgamated to form the present-day State of Alaska.

The oldest rocks in the State are Paleoproterozoic metamorphic rocks. The best documented of these older rocks are located in southwestern Alaska and are part of the Kilbuck terrane. A 2085 Ma zircon from a granitoid in the Kilbuck terrane represents the oldest tightly dated rock in Alaska (e.g., Bradley et al., 2014). These Kilbuck rocks have isotopic signatures that suggest an origin within a continental margin magmatic arc (Miller et al, 1991). Other units that contain detrital and inherited zircons with ages from 2.3 to 2.0 Ga are in east-central Alaska, the southern part of the Brooks Range in northern Alaska, and the Seward Peninsula in northwestern Alaska (Plafker and Berg, 1994), but the rocks themselves are now realized to be much younger (D. Bradley, Bradley Orchards, written commun., 2015).

Geologic evolution of northern and western Alaska: Arctic Alaska and related terranes

The east-west trending Brooks Range of northern Alaska is the northernmost segment of the North American Cordilleran orogen (enclosed map). The regional geology of the Brooks Range has been extensively described by Mull (1982), Moore et al. (1994), and Young (2004). The range is mainly underlain by Neoproterozoic and younger rocks of the Arctic Alaska terrane (Moore et al, 1994), which can be divided in a series of subterranes (Fig. 1) comprising about 25 % of Alaska, and is now viewed as a part of the larger Arctic Alaska-Chukotka terrane that includes the Chukotka Peninsula and Wrangel Island of arctic Russia, as well as the North Slope and Brooks Range of Alaska (Fig. 2). The oldest rocks of the Arctic Alaska terrane consist of at least two deformed Proterozoic to Devonian continental margin sequences amalgamated in Late Devonian to Mississippian time (Strauss et al., 2013). Pre-Carboniferous carbonate and siliciclastic rocks in most of the Brooks Range, Seward Peninsula, and adjacent Russia have faunal affinities with Baltica and Siberia (Blodgett et al., 2002; Dumoulin et al., 2002, 2014) and contain detrital zircon populations that suggest proximity with Baltica (Amato et al., 2009; Till et al., 2014); similar-aged rocks in the northeastern Brooks Range have Laurentian origins and may be a fragment of northeastern Laurentia (Strauss et al., 2013). After juxtaposition of these two or more sequences along the Canadian arctic margin, deposition of carbonate platform and fluvial to continental shelf sediments persisted from Late Devonian-Mississippian through Jurassic mainly along the southern side of this presently

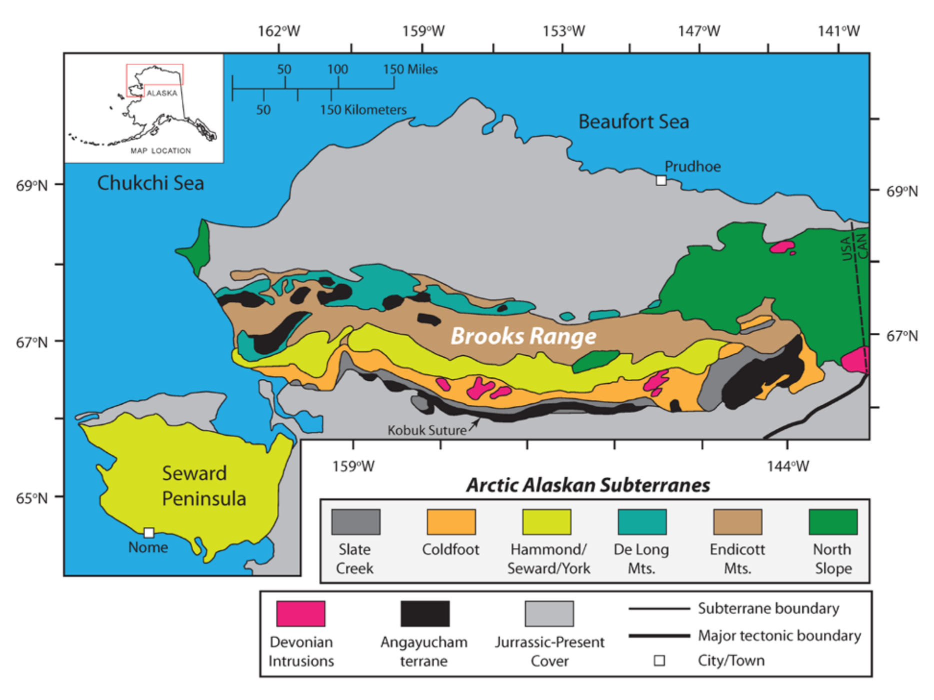


Figure 1. Continental margin subterranes of the Neoproterozoic-early Paleozoic Arctic Alaska terrane, part of the Arctic Alaska-Chukotka microcontinent, which were amalgamated along the Canadian Arctic and now partly form the Brooks Range and buried North Slope basement of northern Alaska. Oceanic rocks of the Angayucham terrane were thrust over the rocks of the Arctic Alaska terrane in Early Cretaceous. After Strauss et al. (2013).

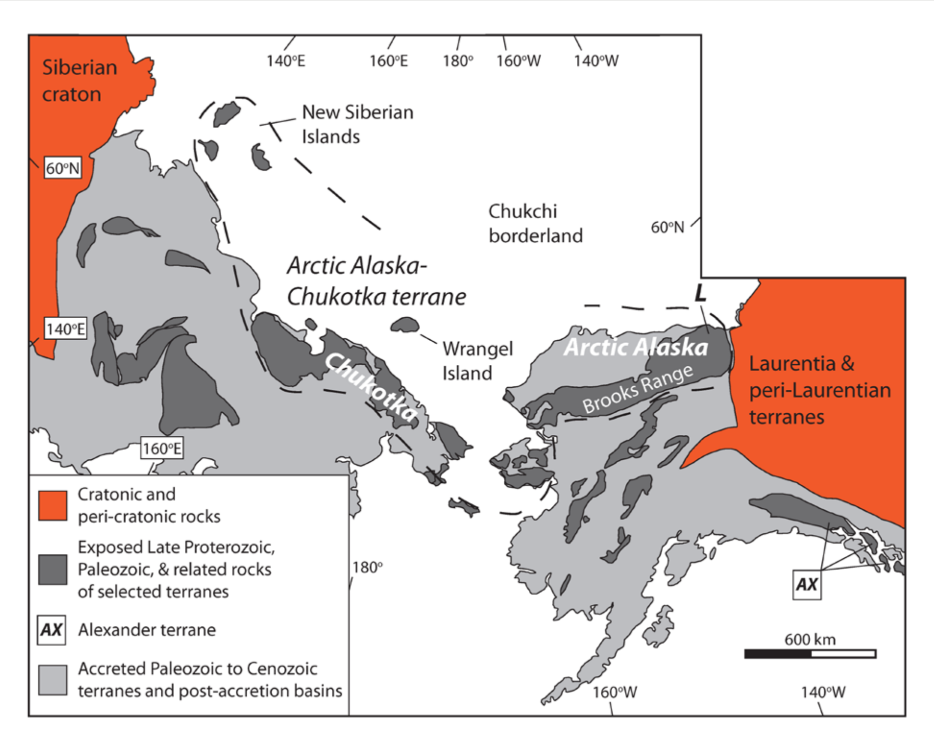


Figure 2. Map showing northwestern North America, northeastern Russia, the extent of the Arctic Alaska-Chukotka microcontinent or terrane and locations of select terranes with Neoproterozoic and early Paleozoic rocks. The letter "L" in the northeasternmost part of the Arctic Alaska-Chukotka terrane shows the area where pre-Devonian rocks with Laurentian affinities are exposed (Strauss et al. 2013). Modified after Till et al., 2014.

east-west-trending terrane. Brooks Range orogeny is marked by the Late Jurassic-Early Cretaceous collision of the Koyukuk oceanic arc with the southern subducting margin of the Arctic Alaska terrane (Plafker and Berg, 1994).

The rocks exposed along the southern flank of the Brooks Range are Mississippian and older (Till, 2008) and were those subducted during the early phases of the Late Jurassic or Early Cretaceous orogenesis (Till et al., 1988; Gottschalk, 1990). These blueschist-facies and exhumation-related greenschist-facies rocks of the informally named Schist belt and its overlying carbonate rocks contain volcanogenic massive sulfide and carbonate-hosted copper deposits, respectively (Hitzman et al, 1986). One structural model for the deformed Arctic Alaska terrane rocks north of the Schist belt is that they are a series of seven or more stacked and fault bounded allochthons (Mayfield et al., 1983) resulting from the deformation associated with the arc-continent collision. The structurally lowest of these, the Endicott Mountains allochthon (or subterrane of Fig. 1), is the host for a number of the large shale/mudstone-hosted massive base metal sulfide deposits in the northwestern part of the range.

The arc-continent collision, in addition, emplaced oceanic rocks of the Angayucham terrane structurally above the continental rocks of the Arctic Alaska terrane (Fig. 1). These obducted rocks from a closing ocean basin consist of an upper assemblage of Middle Jurassic peridotite and gabbro and a lower assemblage of Devonian to Jurassic basalt and pelagic sedimentary rocks (Moore et al., 1994). The emplacement of the oceanic rocks, with their contained occurrences of chromite, was coeval with deformation of the Arctic Alaska terrane into a thin-skinned fold-and-thrust belt.

The Seward Peninsula, to the southwest of the Brooks Range, is also underlain by rocks of the Arctic Alaska-Chukotka superterrane or microplate (Fig. 1). The Nome Complex (Fig. 3) of central Seward Peninsula (Till et al., 2011, 2014) consists of a pre-Carboniferous penetratively deformed continental margin sequence that is correlative with protoliths of the southern Brooks Range Schist belt and rocks of the Endicott Mountains allochthon (Till et al., 2014). The Mesozoic deformational history of the Nome Complex parallels that of the Brooks Range Schist belt, as it was also subducted and metamorphosed dur-

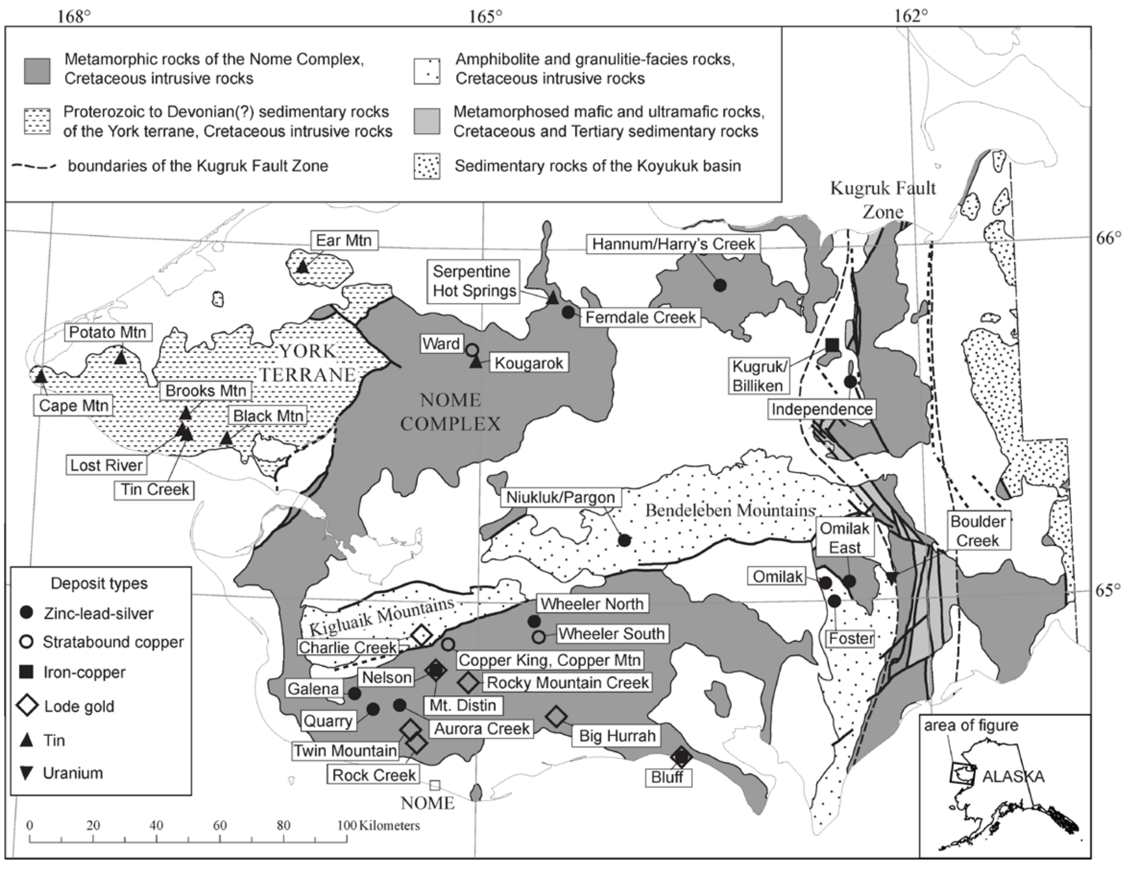


Figure 3. Simplified geologic map of Seward Peninsula showing major metallic mineral deposits. Geology from Till et al. (2011), modified from Slack et al. (2014).

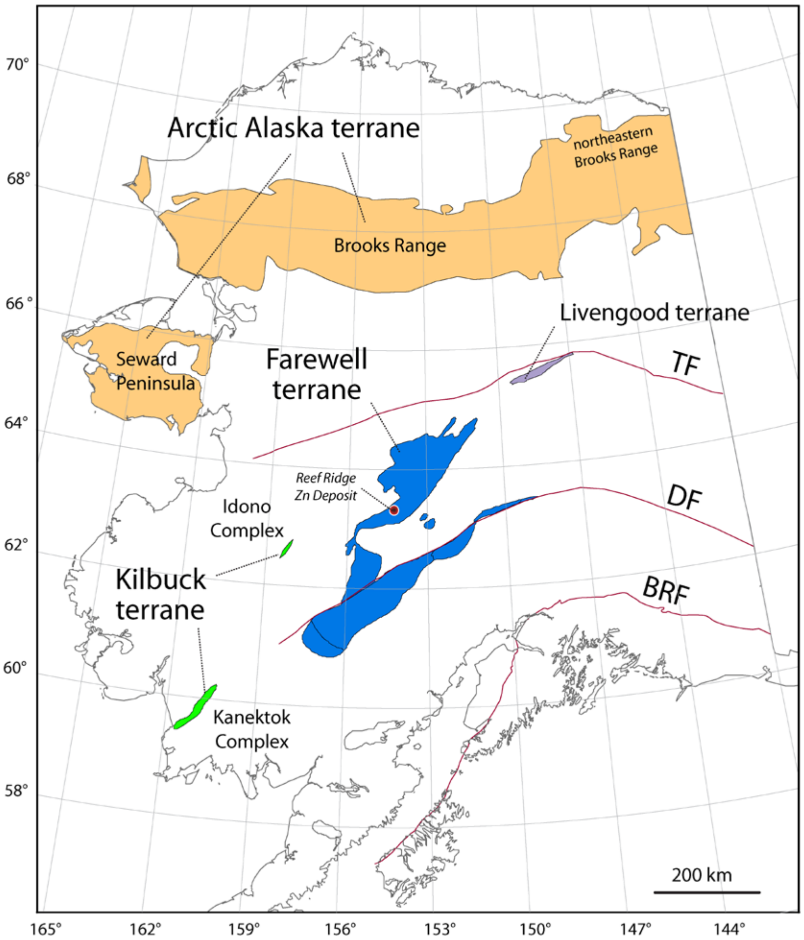


Figure 4. Rocks that were part of the Arctic Alaska terrane through early Paleozoic, probably separating from the microcontinent in Devonian, include those of the Farewell terrane, now in western interior Alaska, and those of the Kilbuck terrane, comprising two areas of Paleoproterozoic rocks in western Alaska. The Farewell terrane also has affinities with the Livengood terrane. Major fault systems fragmenting many of the terranes in Alaska include the Tintina (TF), Denali (DF), and Border Ranges (BRF). The Reef Ridge deposit and related Zn-nonsulfide replacement and veinlet occurrences in the Farewell terrane formed from late Tertiary supergene alteration of older magmatic deposits. After Bradley et al. (2013).

ing the Late Jurassic or Early Cretaceous (Hannula and McWilliams, 1995; Till et al., 2011). The rocks of the Nome Complex host late Early Cretaceous orogenic gold deposits and economically important associated placers. Pre-Devonian non-metamorphosed or slightly metamorphosed carbonate and clastic rocks of the York terrane (Fig. 3) underlie northwestern Seward Peninsula (Dumoulin et al., 2014) and host Late Cretaceous tin granites (Till et al., 2011).

The Farewell terrane in western interior Alaska (Fig. 4), also with Proterozoic basement and a Neoproterozoic to Devonian platform carbonate sequence, is part of the same large early Paleozoic platform that contained the Arctic Alaska terrane somewhere between Laurentia, Siberia, and Baltica. Farewell subsequently rifted apart from the Arctic Alaska-Chukotka microcontinent by Middle Devonian (Bradley et al., 2013). Although lacking any obvious Paleozoic cover rocks, the Paleoproterozoic rocks of the Kilbuck terrane in southwestern Alaska (Fig. 4) were also a part of the microcontinent during its early evolution (Bradley et al., 2013). A vast part of western Alaska, surrounding rocks of the Farewell terrane and south of the Arctic Alaska terrane, is covered by middle to Late Cretaceous terrigenous overlap rocks of the Koyukuk basin and Early Cretaceous andesitic volcanic rocks of the Koyukuk terrane (Patton and others, 1994).

Accreted terranes of southern Alaska

South-central Alaska (Fig. 5) mainly comprises the Wrangellia composite terrane and the seaward Chugach terrane that represents a subduction-accretion complex. The Wrangellia composite terrane (or PAW superterrane), underlying parts of present-day southwestern, south-central, and southeastern Alaska, as well as British Columbia and Yukon, Canada, formed during late Paleozoic amalgamation of the Alexander, Wrangellia, and Peninsular oceanic arc terranes; it underlies about 20 % of the State (Plafker and Berg, 1994). The formation of the composite terrane occurred in Early Permian between a fringing arc system off western North America and the Uralian orogen that sutured Eurasia and Laurentia (Beranek et al., 2014). By early Mesozoic, Wrangellia was transported far to the south of present-day Alaska along the western margin of Laurentia (Hillhouse and Grommé, 1984; Umhoefer, 2003; Goldfarb et al., 2013).

The oldest rocks of the Chugach terrane were accreted to the seaward side of the Wrangellia composite terrane in early Mesozoic before the latter had collided with the continental margin in the middle Cretaceous. Paleomagnetic results suggest that this initial amalgamation took place south of latitude 25° north (Amato et al., 2013). As the terranes moved to the northeast, they collided with North America, as defined by 101-91 Ma mélange sediments of the Chugach terrane. The majority of the Chugach terrane comprises flysch of the Valdez Group, deposited by

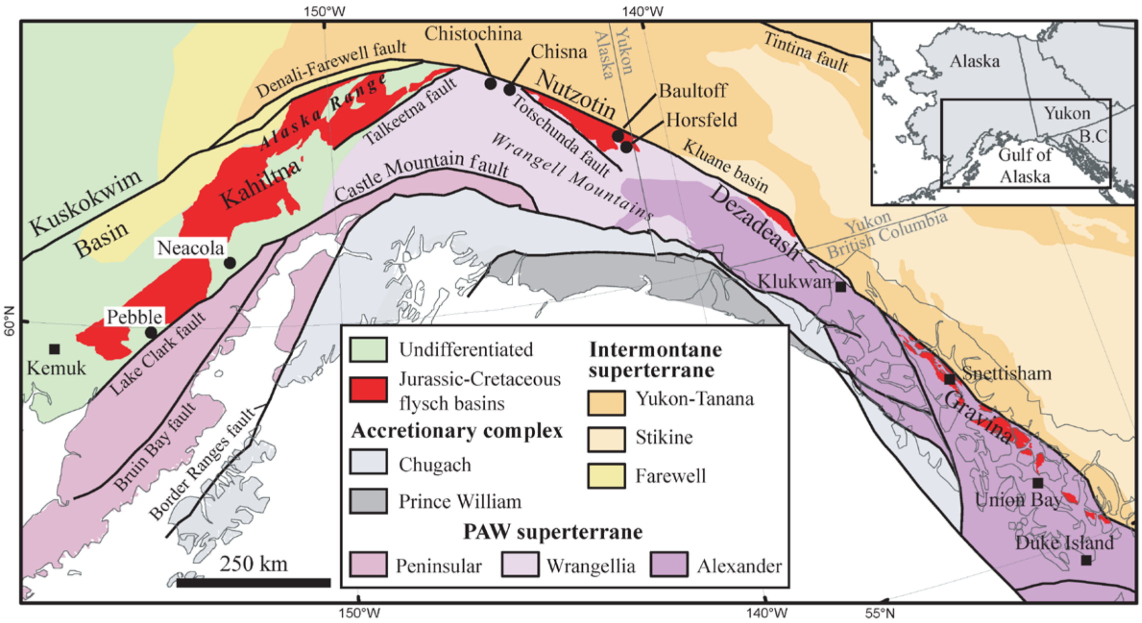


Figure 5. Southern Alaska is dominated by the Wrangellia composite terrane or microcontinent, also referred to as the PAW superterrane. It comprises three distinct oceanic arc terranes (Peninsular, Alexander, and Wrangellia) that were amalgamated in late Paleozoic. The Chugach subduction-accretion complex was added to the seaward margin of the composite terrane when it was located many hundreds of kilometers to the south of its present location. Location of Pebble and other mid-Cretaceous porphyry deposits (solid circles) and zoned Alaskan-type mafic and ultramafic bodies (solid squares) of southern Alaska. The porphyry deposits are related to igneous rocks that intrude flysch basins on the landward side of the Wrangellia composite terrane. After Goldfarb et al. (2013).

turbidite fans from about 75-55 Ma (Amato et al., 2013; Garver and Davidson, 2015). Seaward of the Chugach terrane, the Prince William terrane represents an early Tertiary continuation of the turbiditic sedimentation seaward of the trench. The Yakutat terrane (included as southern part of Prince William terrane on figure 5 and shown later on figure 33A), the youngest accreted block to the south-central Alaska margin, is a piece of southeastern Alaska and adjacent British Columbia that began to subduct below the accretionary complex at about 30 Ma (Bruhn et al., 2004). The Quaternary volcanoes of the Wrangell Mountains formed along the southeastern side of the Alaska Range in the Quaternary as a consequence of the subduction.

The Border Ranges fault zone is the boundary between the Wrangellia arc terrane and the Chugach accretionary complex. More than 600 km of dextral strike-slip along the fault zone is responsible for much of the deformation of the Chugach complex (Pavlis and Roeske, 2007). Mesozoic arcs (e.g., Talkeetna, Chisana, Chitna, Coast Mountains) formed in the southern part of Wrangellia during subduction of the Chugach oceanic crust. Younger flysch-melt granites were emplaced into rocks of the Chugach and Prince William terranes at 61-48 and 39-29 Ma (Hudson et al., 1979; Plafker et al., 1994). Flysch rocks of the accretionary complex range from low to high metamorphic grades, but most of the rocks of the Valdez Group are metamorphosed to greenschist facies.

Pericratonic rocks of eastern Alaska

East-central Alaska (Fig. 6) is defined by pericratonic rocks of the Yukon-Tanana terrane located between the Denali and Tintina strike-slip fault systems, and thus between the seaward Wrangellia and Chugach terranes and Arctic Alaska terrane and related rocks to the north. These pericratonic rocks within the Yukon-Tanana Upland and part of the Alaska Range to the south, which were a part of ancestral North America or Laurentia, have been metamorphosed to greenschist to amphibolite facies. The Neoproterozoic to middle Paleozoic protoliths for the metamorphic rocks were mainly clastic sedimentary rocks, with lesser carbonate and magmatic rocks (Foster et al., 1994). A subduction-related Devonian arc was built upon this attenuating Laurentian continental margin crust, it was rifted in Late Devonian to open the Slide Mountain-Seventymile Ocean, and it was accreted back to the

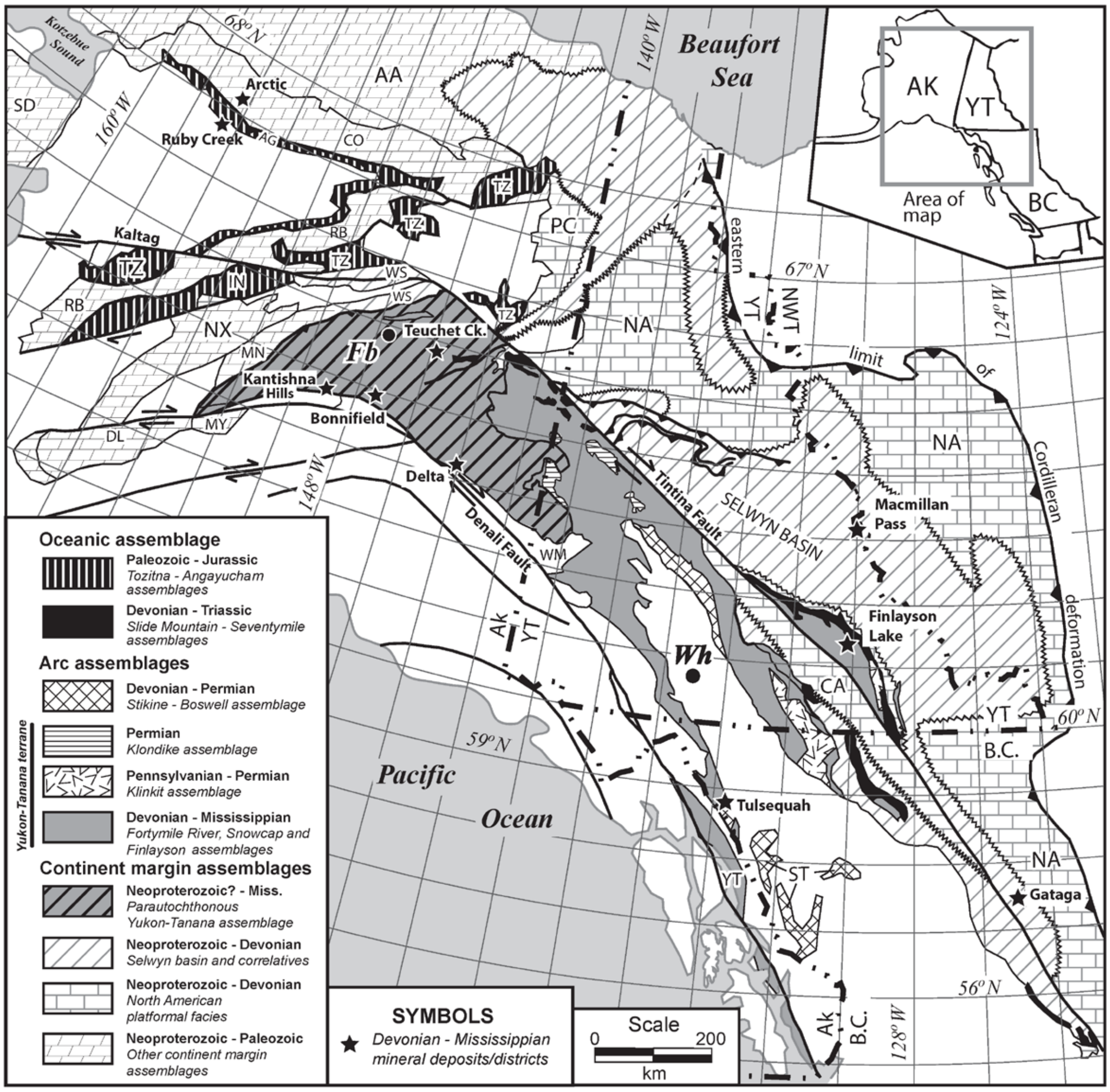


Figure 6. Regional geological map of terranes in eastern Alaska and adjacent Canada. The area is dominated by rocks of the Yukon-Tanana terrane, recently defined by Dusel-Bacon et al. (2013) as composite in nature with arc assemblages reflecting the true allochthonous Yukon-Tanana terrane and distinct parautochthonous continental margin assemblages that include the gold-rich Yukon-Tanana assemblage. Also shown are locations of Devonian-Mississippian massive sulfide deposits, including those of the Bonnifield and Delta districts in Alaska. Terranes include AA- Arctic Alaska, AG- Angayucham, CA- Cassiar, CO–Coldfoot, DL-Dillinger, IN-Innoko, MN-Minchumina, MY-mystic, NA-North American miogeocline, NX-Nixon Fork, PC-Porcupine, RB-Ruby, SD-Seward, ST-Stikine, TZ-Tozitna, WM-Windy-Mckinley , WS- Wickersham. Other abbreviations: AK-Alaska, BC-British Columbia, Fb- Fairbanks, NWT-Northwest Territories, Wh-Whitehorse, YT-Yukon Territory. After Dusel-Bacon et al. (2012).

North American margin in the Early Triassic as the ocean basin closed (Nelson et al., 2013). Dusel-Bacon et al. (2013) stressed the composite nature of the Yukon-Tanana terrane/assemblages, with both allochthonous (arc assemblages of figure 6) and parautochthonous (continental margin assemblages of figure 6) components, the latter being the ancestral non-rifted part of the continent margin that hosts the giant Fort Knox and Pogo gold deposits.

Renewed easterly to northeasterly subduction below the Yukon-Tanana terrane is estimated to have occurred from about 220-179 Ma and 115-95 Ma, with at least 400 km of dextral displacement along each of the Tintina and Denali terrane-bounding faults since mid-Cretaceous (Nelson and Colpron, 2007; Allan et al., 2013). The older subduction is associated with emplacement of Early Jurassic arc plutons at depths of >15 km in rocks of the allochthonous assemblage in easternmost Alaska and into adjacent Yukon, Canada (Dusel-Bacon et al., 2013). Subduction beginning at ca. 115 Ma is associated with the extensive northerly translation of rocks outboard of the Denali fault system on the seaward

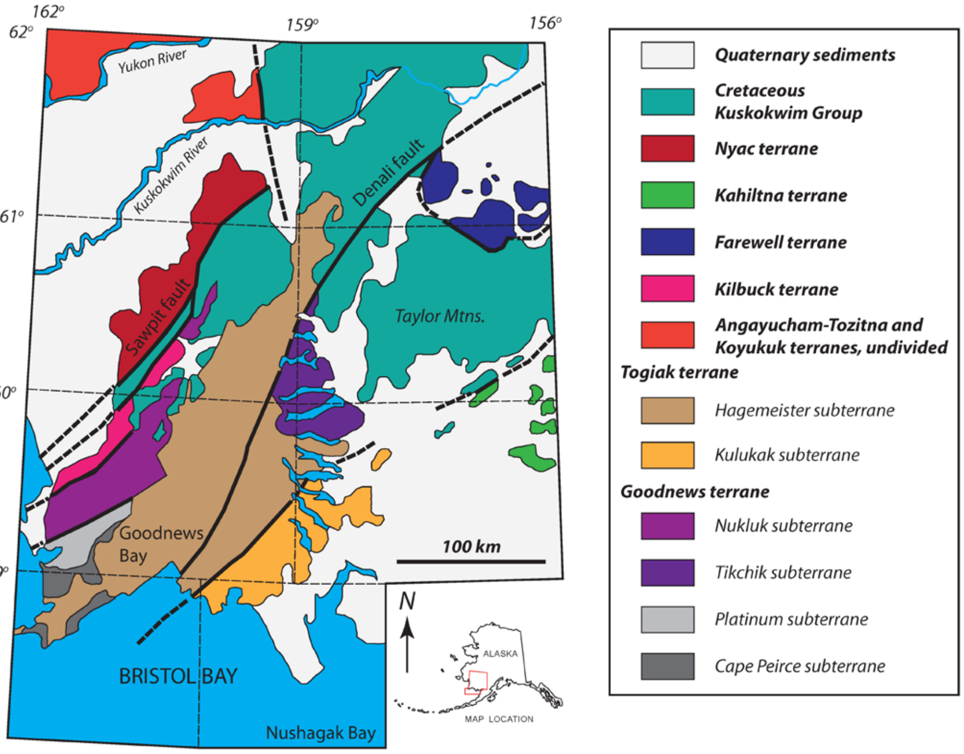


Figure 7. Terrane map and location of Kuskokwim basin in southwestern Alaska (From Miller et al., 2007).

side of the Yukon-Tanana terrane. These rocks comprised the amalgamated Paleozoic to Cretaceous Peninsular-Alexander-Wrangellia terrane (Wrangellia composite terrane) and overlapping Middle Jurassic-Early Cretaceous flysch of the remnant ocean basins between Wrangellia and Yukon-Tanana (Umhoefer, 2003; Pavlis and Roeske, 2007). In present-day coordinates, part of the composite terrane and string of remnant basins lies south of Yukon-Tanana in east-central Alaska and defines much of the eastern Alaska Range.

There was widespread intrusion of middle Cretaceous felsic to intermediate, reduced, and peraluminous granitic rocks in the Yukon-Tanana terrane (Hart et al., 2004b). In the Fairbanks area, the plutons occur as shallowly emplaced (<3-5 km), 94-90 Ma isolated domal bodies; in the Goodpaster district, they are more deeply emplaced (5-9 km: Dillworth, 2007) widespread 109-102 Ma batholiths and ca. 93 Ma smaller bodies. Regional metamorphism in Yukon-Tanana is associated with both Early Jurassic contraction and 135-110 Ma extension that exposed much of the parautochthonous assemblage in the westernmost part of the terrane (Hansen and Dusel-Bacon, 1998). To the south, mid-Cretaceous magmatism along the landward side of the Wrangellia composite terrane included emplacement of felsic to intermediate, oxidized, and metaluminous intrusions.

Kuskokwim basin of southwestern Alaska

The 70,000-km² Kuskokwim basin (Fig. 5, 7) underlies much of southwestern Alaska. The basin has been interpreted as a strike-slip basin formed in response to the Late Cretaceous faulting along the Denali-Farewell fault system to the south and Iditarod-Nixon Fork fault system to the north (e.g., Miller and Bundtzen, 1994; Decker et al., 1994). Most sedimentation took place between 95 to 77 Ma (Miller et al., 2002), when the basin was forming between a series of Middle Jurassic to Early Cretaceous volcanic arc terranes that were approaching the continent from the west and south. To the east of the basin (in present-day configuration), flysch rocks of the slightly older Kahiltna basin (Fig. 5, 7) have an uncertain relationship to the flysch of the Kuskokwim basin (e.g., Graham et al., 2013). Final Kahiltna sedimentation could be as young as 87 Ma (Box et al., 2013). The Kahiltna basin represents the northernmost remnant ocean basin (Fig. 8) closed between Wrangellia and North America (e.g., Hampton et al., 2010). Wrangellia and perhaps the Kahiltna rocks were south of their present latitude until at least ca. 55 Ma

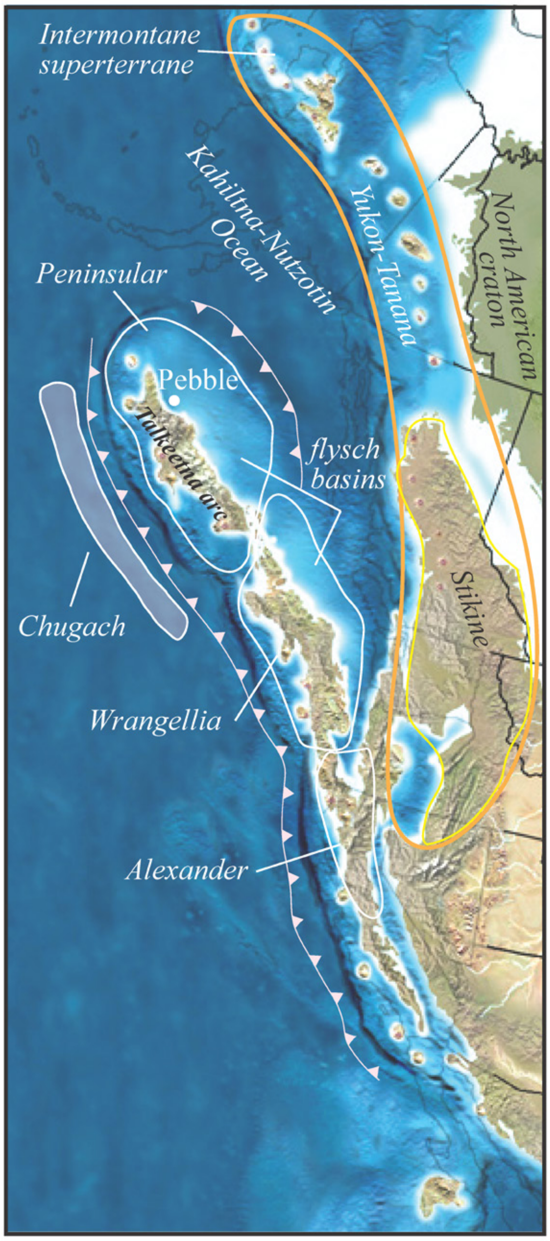


Figure 8. Middle to Late Jurassic paleogeography reconstruction of the continental margin of northwestern North America (modified from Blakely and Umhoefer, 2003 and Goldfarb et al., 20103). The Wrangellia composite terrane and overlapping flysch basins approached the margin at this time, migrating from some unknown location far to the southwest. Paleomagnetic data suggest that at ca. 100 Ma the composite terrane may have been more than 1500 km south of its present-day latitude. Blueschists and mélange of the Chugach terrane began to be added to the seaward margin of the composite terrane at this time.

(Blakely and Umhoefer, 2003). The Kahiltna and Wrangellia rocks have been uplifted to form the present-day western Alaska Range.

The southwestern side of the Kuskokwim basin is bordered by a series of mainly oceanic terranes that were amalgamated with the continent in middle to late Mesozoic (Fig. 7). In addition to the above mentioned old basement rocks of the Kilbuck terrane (Fig. 4), these also include the (1) Late Triassic to Early Cretaceous arc rocks and back-arc volcaniclastics of the Togiak terrane; (2) the Jurassic to Early Cretaceous arc-related volcanic and volcaniclastic assemblage of the Nyac terrane; and (3) the Paleozoic-Mesozoic melange, Permian-Triassic blueschists, and Jurassic mafic and ultramafic rocks of the Goodnews terrane (Decker et al., 1994; Miller et al., 2007). The Cretaceous flysch of the Kuskokwim basin overlaps older rocks of these terranes in many parts of southwestern Alaska.

Most of the clastic rocks in the basins of southwestern Alaska have been metamorphosed to only very low grades. Regional NE-trending fault systems were active during prolonged oblique subduction and host many of the mineral deposits in the region (Bundtzen and Miller, 1997; Graham et al., 2013). Oxidized intermediate to mafic intrusions of the southern Alaska Range plutonic suite of Hart et al. (2004b) were emplaced into both flysch rocks on the seaward side of the Kahiltna basin and rocks of adjacent Wrangellia from about 100-88 Ma. Prior to a second and more widespread magmatic episode beginning at ca. 74 Ma, regional deformation also included development of large E-W-striking fold systems (Miller et al., 2002). Moll-Stalcup (1994) suggested the Campanian and younger magmatism in the Kuskokwim region and adjacent western Alaska Range was part of a Cretaceous-early Tertiary subduction-related continental arc that was as broad as 500 km. In contrast, Bundtzen and Miller (1997) suggested that the young magmatism in the Kuskokwim basin, which was locally alkali-calcic and associated with normal faults, was better classified as back-arc. They also noted a distinct series of similar aged, mainly crustal melt peraluminous granite and alkali-granite sills and dikes that are scattered across the region.

MINING HISTORY OF ALASKA

Except for Alaskan Natives' utilization of native copper, Alaska's mining history is relatively short compared to other arctic regions of the world. The earliest attempt by a non-native to mine was in 1848 in south-central Alaska by P.P. Doroshin, a Russian mining engineer sent to southern Alaska from St. Petersburg by the Russian-American Company (Moffit and Stone, 1906). His two-year effort to mine gold was essentially unsuccessful, but later gold rushes opened up much of the State to mining and development. Early prospectors crossed over Chilkoot Pass from coastal Alaska into the Klondike goldfields in Yukon, Canada (Fig. 9), and then eventually into interior Alaska in the 1880s and 1890s.

Perhaps the most spectacular Alaskan gold rush followed announcement in late 1898 of a significant discovery along the beaches of Nome; in 1899 and 1900 (Fig. 10) as many as 20,000 people flocked to this small town along the coast of the Seward Peninsula in northwestern Alaska. The Nome mining district is the second most important placer district in Alaska, having produced more than 155 tonnes (t) Au, essentially all by placer methods and mostly from complex alluvial deposits or buried beach deposits (Metcalfe and Tuck, 1942; Bundtzen et al., 1994; Athey et al., 2014). Additional Alaskan placer Au discoveries include the Fairbanks (257 t; Fig. 11), Circle (23 t), Fortymile (15 t), Hot Springs (14 t), and Tolovana (16 t) districts in interior eastern Alaska and the Iditarod-Flat (45 t) and Innoko (23 t) districts in southwestern Alaska. Follow-up of small concentrations of alluvial gold in the late 1800s and early 1900s led to discovery of the Alaska-Juneau (Fig. 12A, B), Treadwell (Fig. 12C), and Chichagof deposits in southeastern Alaska and the Willow Creek district deposits in south-central Alaska, Alaska's most significant lode gold producers prior to the 1990s.

Total historic Alaska gold production is likely more than 1400 t, 54 % of which came from placer deposits (Fig. 13). This undoubtedly is a low estimate, as production from small properties often went unreported. In addition, from 1880 through 2013, estimated cumulative Alaskan mining production included about 10,300 t Ag, 1400 t Hg, 5000 t Sb, 3300 t Sn, 2.5 million tonnes (Mt) Pb, 12 Mt Zn, 0.6 Mt Cu, 35,500 t Cr, 600 t U_3O_8, and 21 t Pt (Table 1, Athey et al., 2014; http://wr.ardf.usgs.gov).

The late 1890s gold rushes that brought prospectors into Alaska also led to the discovery of the famous high-grade Kennecott-type copper deposits located in the Wrangell Mountains in the easternmost part of south-central Alaska. A railroad was soon built linking the mines with the seaport of Cordova, and production took place between 1911 and 1938 (Fig. 14), which helped lead to the establishment of the Kennecott Copper Corporation. During that period, 4 Mt of ore grading 13 % Cu yielded about 537,000 t Cu, as well as approximately 100 t Ag. The Kennecott district was incorporated into Wrangell-St. Elias National Park in 1980 and the mine workings designated a National Historic Landmark.

Figure 9. Miners climbing the Chilkoot Pass between Skagway, Alaska and Yukon, Canada, September 1898, during the Klondike gold rush. Image from Per Edward Larss and Joseph Duclos

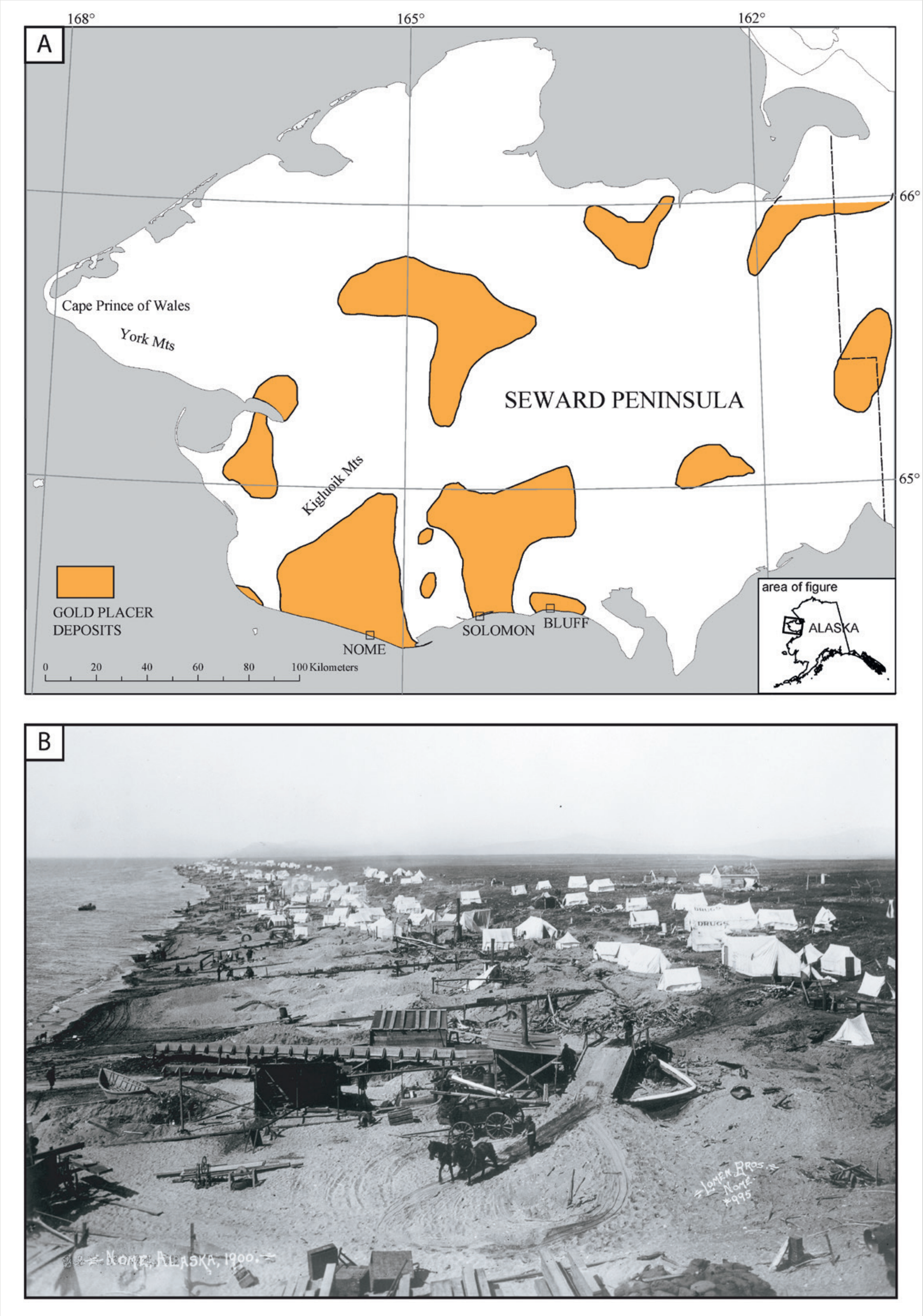


Figure 10. Historic placer mining on the rivers and beaches of the Seward Peninsula near Nome led to recovery of more than 155 t Au. A) Locations of historic placer gold workings on the Seward Peninsula, northwestern Alaska, modified from Nelson and Hopkins, 1972. B) View of the beach west of Nome, 1900. Tents and mining equipment are present. Photography by Loment Bros., Nome.

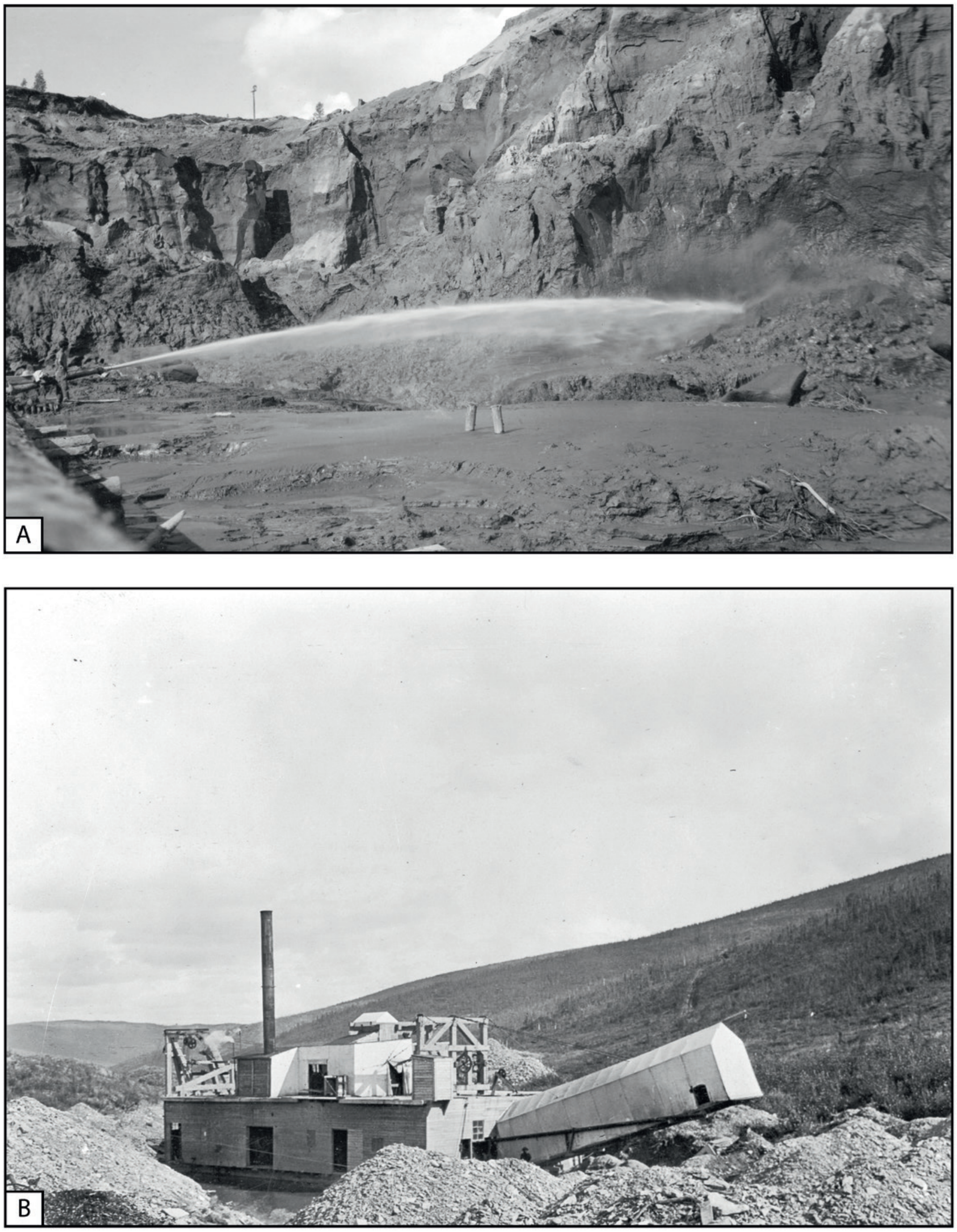


Figure 11. More than 250 t Au were recovered from placer operations in the Fairbanks district, east-central Alaska. A) Hydraulic mining below a 45 m high bank of loess on Cripple Creek, July 31, 1936. B) Fairbanks Gold Mining Company dredge on Fairbanks Creek. Images from Purington (1905).

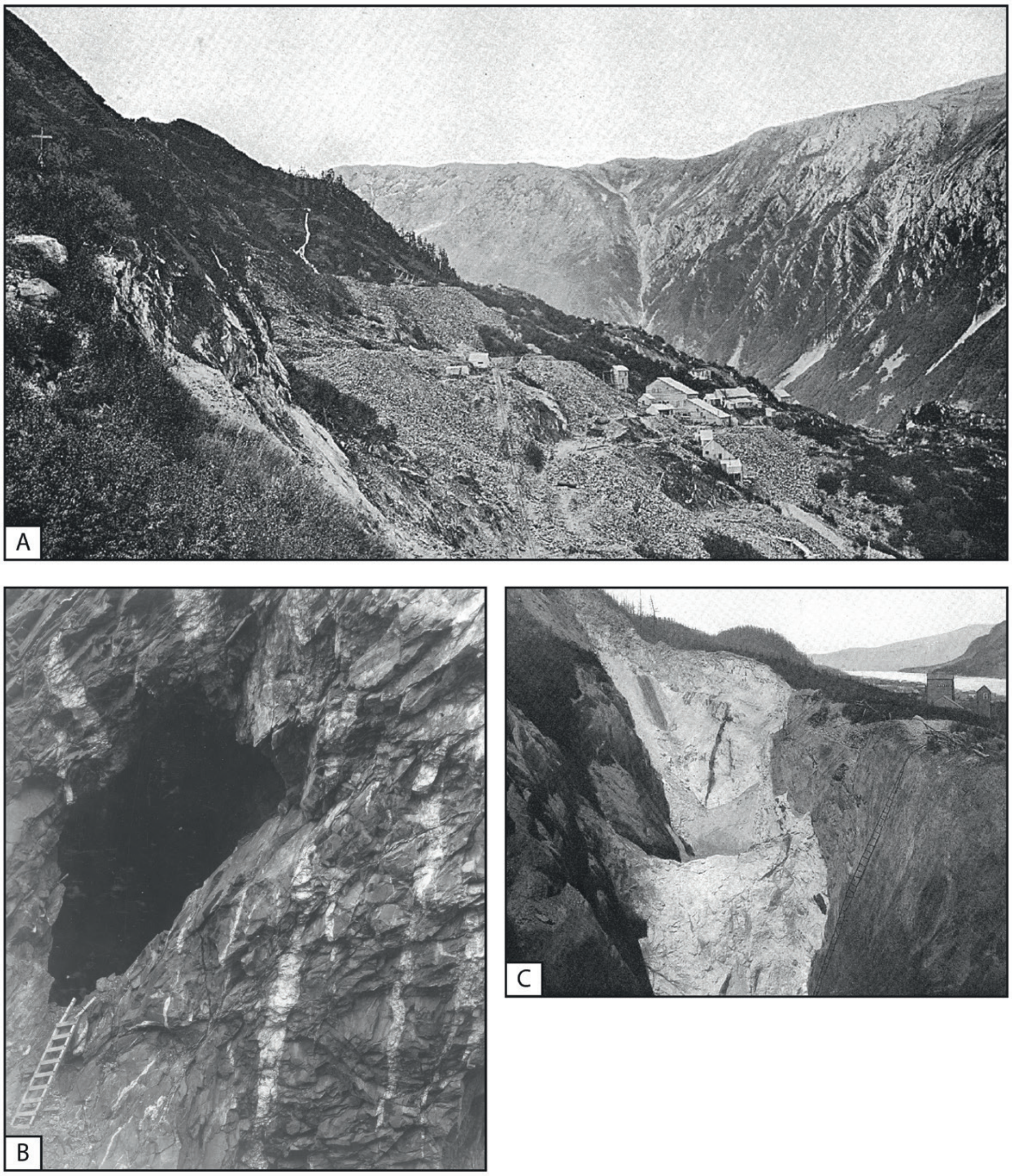


Figure 12. The two major mines of the Juneau gold belt, Alaska-Juneau and Treadwell, were the largest historic gold producers in the state of Alaska. A) Alaska-Juneau mine and mill, in Last Chance basin, southeastern Alaska. B) Fissure veins and underground workings in brown diorite, Ebner mine, Alaska-Juneau deposit. C) The Treadwell mine pit on opposite side of Gatineau Channel from Alaska-Juneau deposit. A cave-in flooded the pit and halted mining in 1917. Images from Spencer (1906).

Base metal deposits were discovered in northwestern Alaska in the late 1960s and exploration took place in the subsequent decades. Iron-oxide staining was first noted along Ferric Creek in the western Brooks Range in 1955 (Koehler and Tikkanen, 1991). Following up on this occurrence, Irv Tailleur, a USGS geologist, sampled stream sediments and rocks along the similar iron-oxide-stained Red Dog Creek (east of Ferric Creek) in 1968 and found >10 % Pb in stream sediments and > 2 % Pb and 1 % Zn in mineralized rock samples (Tailleur et al., 1970). The area was first drilled in 1980 and the second hole intercepted 11.0 m at 48 % Zn and 10 % Pb. Further drilling and ongoing production have established Red Dog as one of the world's largest clastic-dominated Pb-Zn (SEDEX) deposits, accounting for 4 % of the world's and 95 % of U.S. zinc reserves (Athey et al., 2014). Other base metal sulfide deposits are recognized in the Red Dog district and

Figure 13. Locations of significant placer gold accumulations in Alaska and years of earliest discoveries. Image from Yeend et al. (1998).

1834 Party of Russian-Americans under Malakoff reports finding gold in the Russian River drainage of the Kenai Peninsula.
1867 Alaska purchased from Russia and officially handed over to the United States in a ceremony at Sitka.
1880 Gold discovered near Juneau, both in the Silver Bow Basin and on Douglas Island.
1886 Gold found in the Fortymile River, the first major gold discovery in the interior of Alaska.
1893 Gold discovered on Birch Creek in an area that later became famous as the Circle Mining District.
1896 George Washington Carmack, Skookum Jim, and Tagish Charlie find rich deposits of gold on a tributary of the Klondike River in the Yukon Territory of Canada, starting the Klondike Gold Rush.
1898 Miners from the Klondike continue down the Yukon to Alaska's Seward Peninsula and find god at Nome. Others make finds in other parts of Alaska.
1902 Felix Pedro finds gold on a tributary of the Tanana River at the site what is now the city of Fairbanks.

elsewhere in the western Brooks Range, but remain undeveloped.

Additional Alaskan discoveries in the latter half of the 20th century include Quartz Hill in 1974, Greens Creek in 1979, Fort Knox in 1984, Donlin Creek and Pebble (just south of 60°) in 1988, and Pogo in 1994. These deposits are discussed in more detail in later sections. At present Alaska has five active lode mines (Fort Knox, Greens Creek, Kensington, Pogo, and Red Dog) in addition to continuing production from numerous placer gold operations throughout the state. Production data, reported reserves and resources, and total contained metals for the major deposits in Alaska are listed in Tables 2 and 3 for gold and other metals, respectively.

Figure 14. Operations of the Kennecott copper deposits were active in the Wrangell Mountains from 1911-1938. The old Kennecott mill is now preserved as a National Historic Landmark within Wrangell-St. Elias National Park and Preserve.

COMMODITY	PRODUCTION	UNITS	VALUE (MILLION $)	YEARS OF PRODUCTION	NOTES
Gold	44,904,866 (1,396 t)	Troy ounces	11,496.3	1880 to present	Probably low as reporting is likely incomplete.
Silver	330,295,964 (10,272 t)	Troy ounces	3,313.2	1880 to present	
Mercury	40,945 (1,415 t)	76 lb flasks	9.9	1920-1980, 1984-1986	
Antimony	5,032	Tonnes	6.7	1910-1979, 1983-1986	Production data withheld 1920-1929
Tin	3,312	Tonnes	12.5	1900-1993	
Lead	2,488,970	Tonnes	2,993	1880-1980, 1989 to present	
Zinc	11,980,205	Tonnes	18,541	1940-1949, 1989 to present	
Platinum	673,548 (21 t)	Troy ounces	74.4	1910-1976, 2011	Production data are not available for 1950 to 1976, hence numbers could be quite low. Intermittent low or withheld production 1981-1996
Copper	634,088	Tonnes	245.3	1900-1969, 1996-2002, 2007, 2011 to present	
Chromium	35,501	Tonnes	3.4	1910-1919, 1940-1959, 1970-1979	
Uranium, (U_3O_8)	604	Tonnes	n.a.	1957-1991	

Table 1. Total production – Alaska 1880 to 2013 (Athey et al., 2014), Uranium from ARDF data (http://wr.ardf.usgs.gov).

DEPOSIT	LATITUDE (N)	LONGITUDE (W)	DISTRICT	DEPOSIT TYPE	YEARS OF PRODUCTION	AU PRODUCTION (TONNES)
Alaska-Juneau	58.308	134.342	Juneau Gold Belt	Orogenic	1883-1944	95.5
Apollo	55.191	160.563	Shumagin Islands	Epithermal	1892-1904, 1908-1913	4
Chichagof	57.663	136.098	Chichagof	Orogenic	1906-1942	18.7
Cleary Hill	65.067	147.439	Fairbanks	Orogenic	1910-1915, 1929-1932	3
Donlin Creek	62.043	158.209	Kuskokwim	Orogenic(?)	undeveloped	
Fort Knox	64.992	147.361	Fairbanks	Intrusion-related	1996-present	181
Independence	61.792	149.294	Willow Creek	Orogenic	1909-1942, 1949-1951	5.3
Kensington	58.864	135.082	Juneau gold belt	Orogenic	1897-1900, 2010-present	12.6
Lucky Shot/War Baby	61.779	149.408	Willow Creek	Orogenic	1922-1942	7.1
Money Knob	65.509	148.534	Livengood/Tolovana	Intrusion-related(?)	undeveloped	
Pogo	64.453	144.914	Goodpaster	Orogenic	2006-present	approx 90
Treadwell	58.269	134.378	Juneau Gold Belt	Orogenic	1882-1923	91.6

Note: Data from USGS Alaska Resource Data Files and other references cited

Table 2. Past production and reserves/resources for significant lode gold deposits in Alaska.

GOLD GRADE (GRAMS/TONNE)	OTHER METALS PROD. (TONNES)	GOLD RESERVES (TONNES)	GOLD RESOURCE (TONNES)	GOLD GRADE (GRAMS/TONNE)	REFERENCES
1.6	77.5 t Ag, 20,321 t Pb		approx 150	1.25	Redman et al. (1991)
8		20		24	Freeman (2015)
approx 30	5.5 t Ag		minor		
40					
		964	142	2.1	www.novagold.com
0.9		68	45	0.45	Freeman (2015)
approx 35	minor W				
5.8	possibly Te	18	27	5.8	www.coeur.com
probably >30	minor Cu		minor		
			570	0.58	www.ithmines.com
14	minor Ag	51	77	11.5	Freeman (2015)
3.6	5.1 t Ag		significant		Redman et al. (1991)

DEPOSIT	LATITUDE (N)	LONGITUDE (W)	DEPOSIT TYPE	YEARS MINING	PAST PRODUCTION	METAL GRADES	RESERVE (CONTAINED METAL)	GRADE
Anarraaq	68.155	163.033	Clastic-dominated Pb-Zn					
Arctic	67.174	156.3875	VMS					
Beatson	60.0493	147.8995	VMS	1908-1930	0.083 Mt Cu, 41.5 t Ag	1.65% Cu, 8.7 g/t Ag		
Bond Creek	62.198	142.7027	Porphyry					
Bornite (Ruby Creek)	67.0624	156.948	Carb. Copper					
Brady Glacier	58.5533	136.9275	Magmatic Ni-Cu					
Death Valley (Boulder Ck)	65.0507	162.2467	Sed. Uranium					
Greens Creek	58.079	134.6312	VMS	1989-1993, 1996-present	1.36 Mt Zn, 0.43 Mt Pb, 42 t Au, 5180 t Ag	approx. 11% Zn, 4% Pb, 3.4 g/t Au, 500 g/t Ag	0.62 Mt Zn, 0.23 Mt Pb, 20 t Au, 2622 t Ag	8.7% Zn, 3.3% Pb, 372 g/t Ag, 2.8 g/t Au
Kemuk (Humble)	59.7203	157.67	Urals-Alaska type complex					
Kennecott	61.522	142.821	Kennecott-type copper	mainly 1911-1938	0.54 Mt Cu, approx 100 t Ag	approx. 13% Cu		
Klukwan	59.42	135.88	Urals-Alaska type complex					
Lakeview/ Longview	68.6066	157.4783	Sed. Barite					
Lost River	65.474	167.156	Skarn	1952-1956	314 t Sn	1.42% Sn		
Nixon Fork	63.2381	154.7759	Skarn	1918-1964, 1995-1999, 2007, 2011-2013	6.1 t Au, 1200 t Cu, minor Ag	approx 40 g/t Au, 0.9% Cu		
Orange Hill	62.204	142.8449	Porphyry					
Pebble	59.8991	155.2807	Porphyry					
Quartz Hill	55.403	130.483	Porphyry					
Red Dog	68.0704	162.8379	Clastic-dominated Pb-Zn	1989- present	11.3 Mt Zn, 2.0 Mt Pb, 3730 t Ag	20% Zn, 5.6% Pb, 90 g/t Ag	7.9 Mt Zn, 2.4 Mt Pb, 2970 t Ag	15.8% Zn, 4.1% Pb, 65 g/t Ag
Red Devil	61.75947	157.31375	Epizonal Hg-Sb	1933-1946, 1953-1963, 1969-1971	1255 t Hg, minor Sb	1.5% Hg		
Red Mountain (Dry Creek)	63.92	147.38	VMS					
Red Mountain	59.35	151.49	Magmatic chromite	1920, 1942-1958	approx 14,000 t Cr_2O_3	38-43% Cr_2O_3		
Whistler	61.9638	152.6799	Porphyry					
WTF	63.92	147.38	VMS					

Note: Presently active mine production data estimated through end of 2014; resources include inferred, except for Red Dog and Greens Creeks where they are measured/indicated; data from USGS Alaska Resource Data Files and other references cited

Table 3. Resources in base metal deposits and occurrences in Alaska.

		TOTAL METAL (COMBINED PRODUCTION, RESERVES, AND RESOURCES)						
RESOURCE (CONTAINED METAL)	METAL GRADES	GOLD T	SILVER T	ZINC MT	LEAD MT	COPPER MT	CU EQUIV. MT	REFERENCE
2.7 Mt Zn, 0.82 Mt Pb, 1125 t Ag, 1000 Mt barite	15.8% Zn, 4.8% Pb, 65 g/t Ag		1125	2.7	0.82			Athey et al. (2014)
0.89 Mt Cu, 1.19 Mt Zn, 0.2 Mt Pb, 177 t Au, 1285 t Ag	3.3% Cu, 4.5% Zn, 0.8% Pb, 0.7 g/t Au, 53 g/t Ag	177	1285	1.19	0.2	0.89		Wilkins et al. (2013)
some ore reported remaining			41.5			0.083		
1.5 Mt Cu, minor Ag, Au, Mo	0.30% Cu					1.5		
2.74 Mt Cu	1.6% Cu					2.74		Davis et al. (2014)
0.46 Mt Ni, 0.27 Mt Cu, 7 t PGEs	0.5% Ni, 0.3% Cu, 0.18 ppm PGE					0.27		
453 t U_3O_8	0.27% U_3O_8							
0.051 Mt Zn, 0.023 Mt Pb, 266 t Ag, 2 t Au	7.3% Zn, 3.3% Pb, 381 g/t Ag, 2.8 g/t Au	64	9068	2.03	0.68			Athey et al. (2014)
384 Mt Fe, also Ti, P	15-17% Fe							
			100			0.54		
535 Mt Fe, also Pt, Pd	16.8% Fe							
33.2 Mt barite								
54,600 t Sn	0.26% Sn							Hudson and Reed (1997)
4.8 t Au		10.9						Athey et al. (2014)
1.36 Mt Cu, 45 t Au, 90 t Ag, minor Mo	0.35% Cu	45	90			1.36		
37 Mt Cu, 2.5 Mt Mo, 3033 t Au, 14,572 t Ag	0.24-0.42% Cu, 0.26-0.35 g/t Au, 1.19-1.66 g/t Ag, 215-250 ppm Mo	3033	14572			37		www.northern dynastyminerals.com
2.03 Mt Mo	0.127% Mo							Ashleman et al. (1997)
1.9 Mt Zn, 0.57 Mt Pb, 1038 t Ag	25.7% Zn, 6.9% Pb, 125 g/t Ag		7738	21.1	5			Athey et al. (2014)
0.13 Mt Zn, 0.055 Mt Pb, 273 t Ag, 1.5 t Au	4.4% Zn, 2.5% Pb, 94 g/t Ag, 0.5 g/t Au	1.5	273	0.13	0.055			Dusel-Bacon et al. (2010)
1.36 Mt Cr_2O_3	mainly 5-6% Cr_2O_3							Foley et al. (1997)
89 t Au, 375 t Ag, 0.35 Mt Cu	0.44 g/t Au, 1.8 g/t Ag, 0.16% Cu	89	375			0.35		www.brazilresources.com
0.17 Mt Zn, 0.07 Mt Pb, 501 t Ag, 2.5 t Au	6% Zn, 2.5% Pb, 179 g/t Ag, 0.9 gt Au	2.5	501	0.17	0.07			Dusel-Bacon et al. (2007)

METALLOGENIC AREAS OF ALASKA

Northern Alaska

Clastic-dominated Pb-Zn (SEDEX) deposits

Clastic-dominated Pb-Zn deposits are those traditionally referred to as sedimentary-exhalative (SEDEX), many of which however lack definitive evidence of exhalative processes (Leach et al., 2010). The Pb-Zn ores are mainly hosted in the structurally lowest Endicott Mountains allochthon or subterrane in the western Brooks Range (Fig. 15A). They mostly occur in relatively non-metamorphosed, fine-grained Mississippian clastic rocks, turbiditic carbonate rocks, and chert at the top of the Kuna Formation within the Lisburne Group (Fig. 15B). The clastic rocks include black siltstone, and siliceous and carbonaceous mudstone and shale. The upper part of the Kuna Formation that hosts all sulfide deposits in the Red Dog district has a total thickness of 30-240 m (Dumoulin et al., 2004). Deposition occurred in a late Early to Late Mississippian anoxic to euxinic basin isolated from the open ocean (Johnson et al., 2015) with limited siliciclastic input and significant amounts of organic carbon; carbonate turbidites derived from adjacent carbonate platforms are locally present in the Kuna Formation (Dumoulin et al., 2004).

Based on contained Zn+Pb, **Red Dog** (Very Large [1])is one of the world's largest clastic-dominated Pb-Zn type deposits. The mine at Red Dog has recovered ore from two orebodies or deposits: the Main deposit (mined out in 2012) and the Aqqaluk deposit (currently being mined). The Qanaiyaq (or Hilltop) and Paalaaq deposits are potential sources of near-term higher-grade ore to supplement the reserves currently being mined from the adjacent Aqqaluk pit (Fig. 16A, B) (Athey et al., 2014). Collectively, the four orebodies are referred to as the Red Dog deposits of Kelley and Jennings (2004). The four deposits at Red Dog have a cumulative reserve and resource of 140.6 Mt of 16.6 % Zn and 4.6 % Pb. Also within the broader Red Dog district are important unmined resources of Zn+Pb at **Su-Lik** (Very Large) and **Anarraaq** (Very Large). A recent estimate indicates a combined pre-mining estimate for all district deposits of 171 Mt containing 15.7 % Zn, 4.5 % Pb, and 82.6 g/t Ag (Blevings et al., 2013). Numerous barite bodies, some associated with the Zn-Pb deposit, are scattered throughout the district and include an estimated 1000 Mt of barite at Anarraaq.

Ore minerals in the Zn-Pb-Ag deposits of the Red Dog district include sphalerite, galena, pyrite, and marcasite (Kelley et al., 2004b). Copper-bearing sulfide phases are rare. Mineralization styles for the base metal sulfides include vein (Fig. 16C), massive (Fig. 16D), breccia, and disseminated. The Anarraaq deposit northwest of Red Dog formed by replacement of carbonate turbidites that are present as layers within the mudstone sequence. The Red Dog deposit ores are very coarse-grained and may be brecciated, whereas deposits such as Anaarraq and Lik-Su are predominantly characterized by extremely fine-grained sulfide layers. Due to post-mineralization deformation during the Brookian orogeny, the Red Dog deposits are structurally separated in a series of thrust slices of siliceous shale and chert. A paragenesis for ore formation is detailed as follows: (1) dominantly barite, with volumetrically minor brown sphalerite and minor galena and pyrite deposition in unconsolidated mud below the ocean floor; (2) yellow-brown sphalerite, galena, and pyrite deposition and recrystallization and coarsening of early barite; (3) red-brown sphalerite, with galena, pyrite, and marcasite, deposited in veins and replacing older barite; and (4) deposition of post-ore sulfides and formation of tan sphalerite breccias (Kelley et al., 2004b). The bulk of the Red Dog ore is the massive to semi-massive yellow-brown sphalerite of the 2nd stage, although 20 % of the zinc ore is in veins as red-brown sphalerite. Kel-

[1] The sizes of the deposits described in this chapter are grouped according to the criteria described by Eilu et al. (2007).

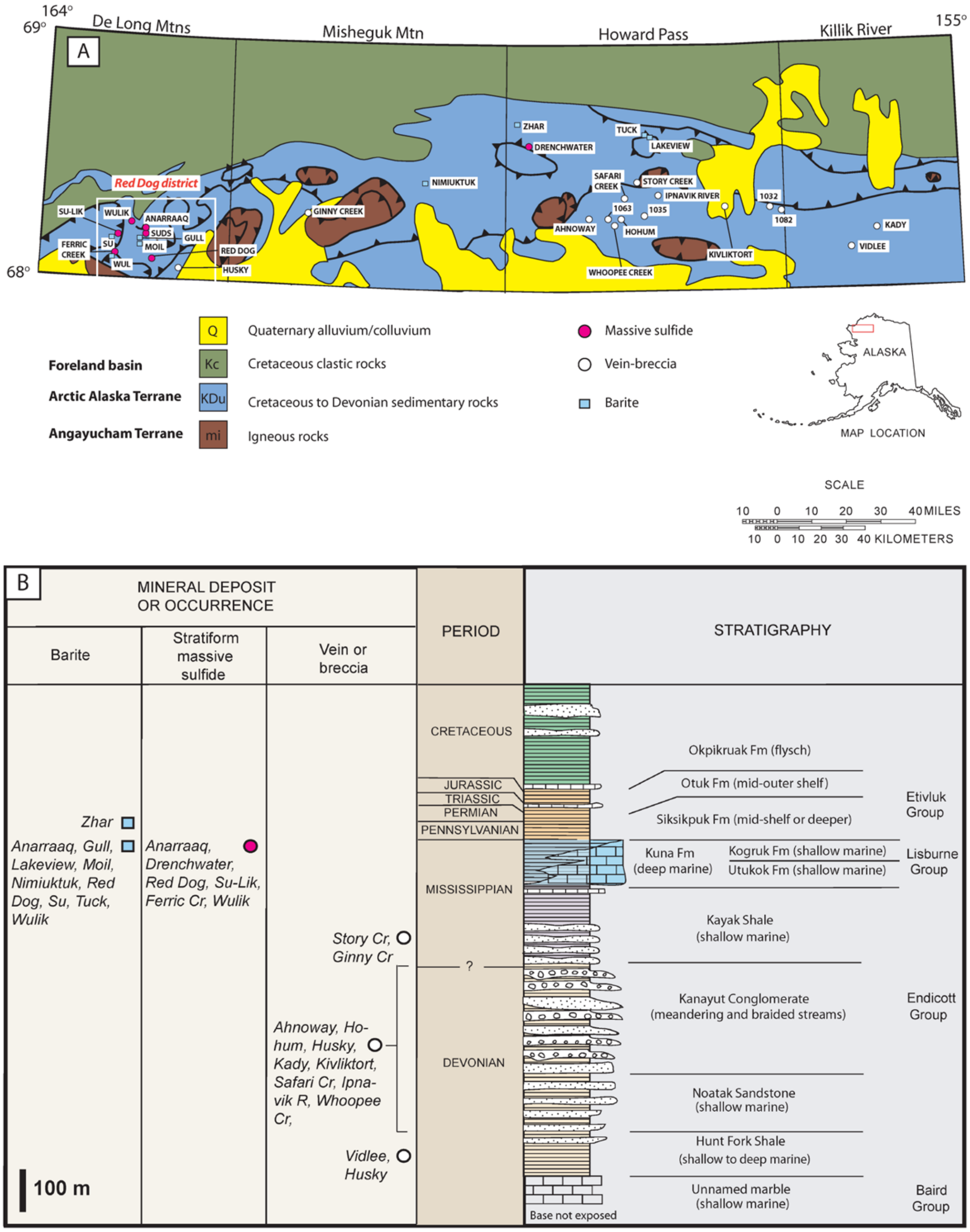


Figure 15. A) Map of the generalized geology of northern Alaska showing locations of mineral deposits in the western and central Brooks Range and outline of the Red Dog. Modified from Mull et al. (1987) and Kelley and Jennings (2004). B) Stratigraphic column for the southern Brooks Range showing locations of barite and base metal-rich mineral deposits. Modified from Kelley and Jennings (2004).

ley et al. (2004b) described a Zn:Pb metal zoning in the Red Dog deposits of 4.5 at the base to 3.0 at the top. Although pyrite is not particularly abundant, Slack et al. (2004) indicated that it contained exceptionally high amounts of Tl, locally as great as 1.2 %. Graham et al. (2009) suggested that Tl may serve as the best geochemical pathfinder in exploration for clastic-dominated Pb-Zn deposits in the western Brooks Range.

Barite and quartz are the main gangue phases in the Red Dog ore. Minor calcite and apatite also have been observed. Quartz is atypically abundant in the Red Dog deposits relative to most clastic-dominated Pb-Zn deposits. Leach et al. (2004) argued that the widespread silicification occurred during the Brookian orogeny, ca. 200 m.y after ore deposition, although Slack et al. (2004) argued some of the quartz was pre- and syn-ore.

Fluid inclusion studies by Leach et al. (2004) showed ore fluid salinities as high as 30 wt. % NaCl equiv. in supratidal evaporative brines,

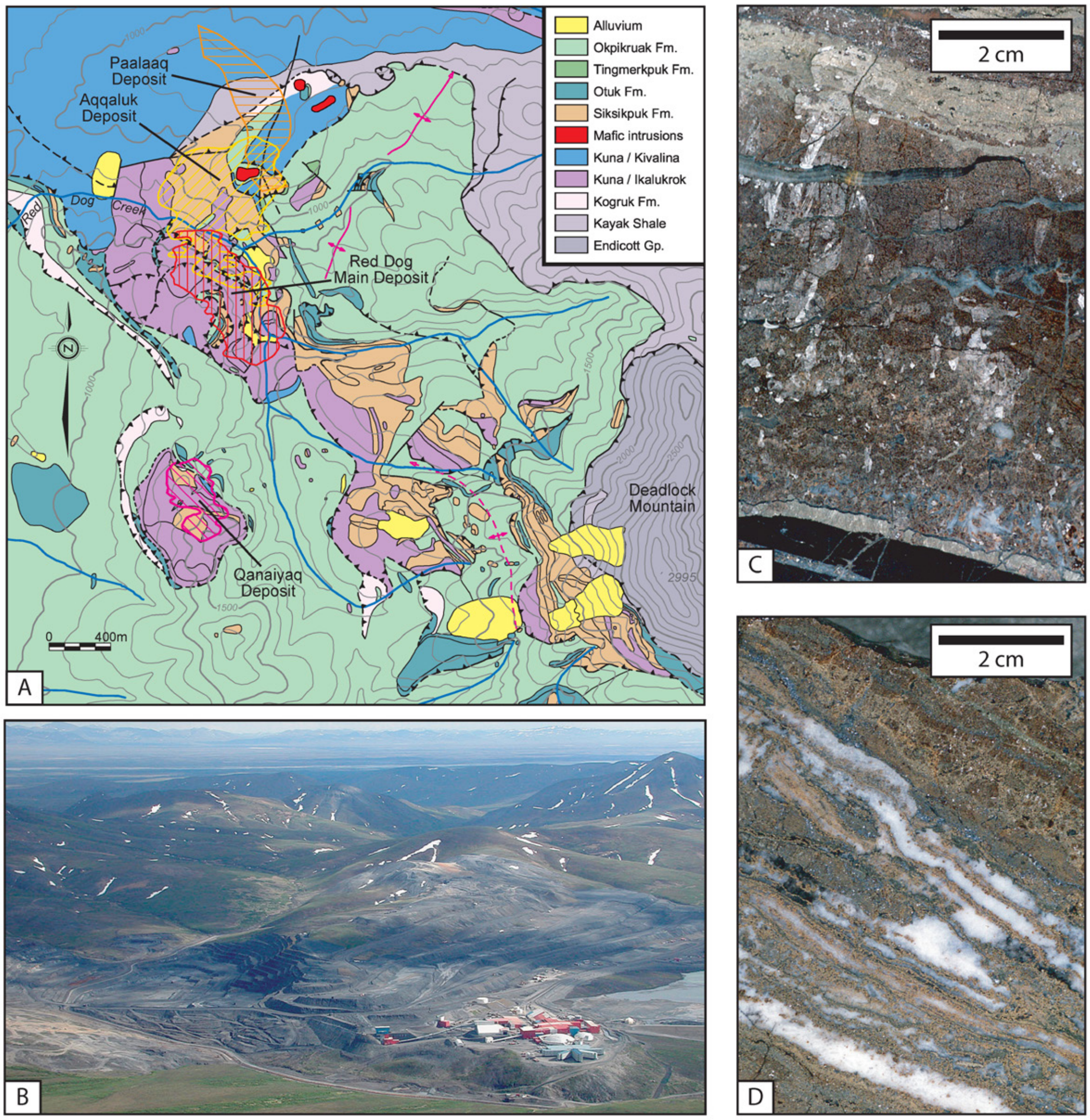


Figure 16. A) Geologic map of the area hosting the Red Dog deposits: Qanaiyaq, Main, Aqqaluk, and Paalaaq. Modified from Kelley and Jennings (2004). B) Aerial photo of Red Dog mine. C) Vein ore at Red Dog. D) Massive sulfide ore at Red Dog. Photos 16 C and 16D courtesy of Karen D. Kelley.

which were generated at a paleolatitude much lower than that of present day Alaska (Lewchuk et al., 2004). The fluid inclusion data also showed ore deposition between 100 and 200°C and at no more than 150 bars, before burial to depths of as much as 12 km during Mesozoic orogeny. Leach et al. (2004) pointed out that these data differ from all previous fluid inclusion data from Red Dog, which indicated hotter, deeper, and less saline fluids, because previous studies did not recognize that much of the studied quartz was not part of the Carboniferous ore event.

Pyrite from the main stage of mineralization at Red Dog was dated by a 10-point Re-Os isochron of 338.3±5.8 Ma (Morelli et al., 2004). This is roughly the age of deposition of the Osagean to early Chesterian (ca. 347-330 Ma) ore host rocks (Dumoulin et al., 2004). Thus, although ore textures clearly show replacement textures, such replacement occurred soon after sedimentation. Rhenium-Os isotopic measurements on sphalerite were not successful probably because of disturbances of the system by later hydrothermal events and/or the Brookian deformation. Such hydrothermal overprinting is further suggested by Jurassic-Cretaceous $^{40}Ar/^{39}Ar$ ages of hydrothermal ore-related white micas from the Red Dog and Anarraaq deposits (Rombach and Layer, 2004).

The barite bodies mentioned above may or may not be spatially or temporally associated with the massive sulfides. In some places within the district, barite and sulfide orebodies are spatially superimposed (e.g., Red Dog deposits) and at others they are spatially distinct (e.g., Anarraaq deposit contains barren barite separated from the underlying sulfide orebody by ~70 m of unmineralized black shale). In all studied examples, barite formed prior to sulfide mineralization (Kelley and Jennings, 2004). All the stratiform barite deposits recognized in the Red Dog district are present along the contact between the fine-grained clastic rocks of the Carboniferous Kuna Formation and the mid-shelf or deeper shale and chert of the Late Carboniferous Siksikpuk Formation (Kelley et al., 2004a). The barite bodies, mainly hosted by the limestone and chert along the contact, are as thick as 145 m. Narrow veins and lenses of barite are also present up-section in sedimentary rocks as young as Triassic. The stratiform barite in the Red Dog district formed during a brief period of ventilation and oxidation of the deep Kuna basin late in its overall history but prior to sulfide formation (Johnson et al., 2015). In contrast, Reynolds et al. (2015) argued that the ore-hosting sediments were deposited in a shelf setting in which redox conditions were affected by a fluctuating oxygen minimum zone and that trace fossils may have played an important role in controlling the flow of ore-forming fluids by increasing host sediment permeability.

The Pb-Zn deposits of the Red Dog district formed in large part by replacement of sub-seafloor strata (Kelley et al., 2004b; Leach et al, 2004, 2005), and not exhalation on the seafloor (e.g., Moore et al., 1986). Extensional tectonism likely initiated fluid flow beneath the isolated basin floor. Metals were scavenged by brines from Devonian to Mississippian underlying clastic rocks of the Endicott Group or deeper fractured basement rocks and the metalliferous fluids moved upward along the extension-related faults (Leach et al., 2004). Zinc-Pb-Ag ores were subsequently deposited in permeable parts of the stratigraphy where the infiltrating fluids were H_2S-rich (Johnson et al., 2015). The H_2S was supplied by reduction of pore water sulfate or dissolution of pre-existing barite (Kelley et al., 2004b). Sulfide deposition was mainly via fracture filling and replacement within the calcareous or carbonaceous rocks and the barite.

Similar, but smaller Zn-Pb-Ag deposits are exposed to the east of the Red Dog district for slightly more than 300 km (e.g., Werdon et al., 2004). The most significant of these is **Drenchwater**, located 140 km east of the Red Dog district and also hosted by rocks of the Kuna Formation

Figure 17. Mounds of Mississippian massive barite (light gray areas) are scattered throughout the western Brooks Range and may be distal products of the large Zn-Pb-Ag hydrothermal systems.

(Fig. 15). Unlike the Red Dog district, igneous rocks are present in the area of the Drenchwater deposit and include trachyte, andesite and basalt, which led workers to originally suggest the deposit was a VMS (e.g., Nokleberg and Winkler, 1982). Barite is absent at Drenchwater (Werdon, 1996). Disseminated mineralization is continuous for 3 km along strike and more local semi-massive mineralization is mottled and brecciated (Schmidt, 1997). Ore minerals are light to brown sphalerite, galena, marcasite, and pyrite in a siliceous matrix.

In addition to the occurrences in mudstone and shale, banded sulfide-rich Zn-Pb-Ag veins and breccias are hosted by more coarse-grained clastic lithologies (e.g., Kelley et al., 1997), which are lower in the stratigraphy than rocks of the Kuna Formation. In such vein-breccias, higher grades of copper are present. Also throughout this belt to the east of Red Dog, more distal mounds of barite (Fig. 17) are scattered across the southwestern Brooks Range, such as at **Lakeview** (Fig. 15, Table 3).

Volcanogenic massive sulfide deposits

The Ambler district (Fig. 18), hosted in the Schist belt, contains a series of VMS deposits that continue for more than 100 km along strike, parallel to the southern margin of the range (Hitzman et al., 1986). The deposits are associated with Middle to Late Devonian bimodal volcanic rocks, particularly schistose metarhyolites, that were likely rift-related and hence are older than the Pb-Zn deposits discussed above. Hitzman et al. (1986) argued that the presence of shallow-wa-

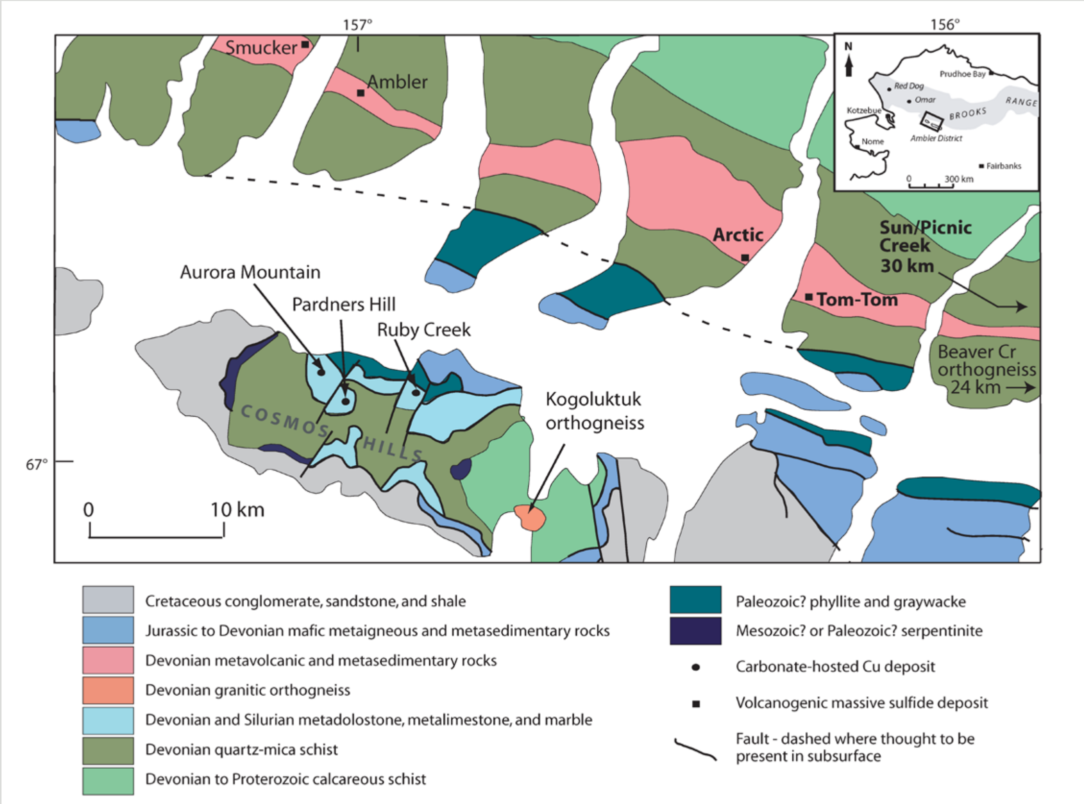


Figure 18. Geologic map of the Ambler polymetallic sulfide district, southern Brooks Range, showing location of carbonate hosted deposits and major volcanogenic massive sulfide deposits. Map revised from Selby et al., 2009.

ter fossils associated with carbonate rocks and volcanic units, most likely formed subaerially, were consistent with ore formation in shallow environments. The VMS deposits are hosted by greenschist facies rocks of the Ambler Sequence of Hitzman et al. (1982), which is dominantly a calcareous and volcaniclastic sedimentary unit that contains abundant rhyolite and basalt flows and tuff. The lowest of three tuff units in the sequence, the 80-m-thick Arctic tuff (Hitzman et al., 1986), hosts the majority of the VMS mineralization.

Arctic (Very Large) is the most significant of these Schist belt deposits (Schmidt, 1986), although none of the deposits have any production. The Arctic deposit (Fig. 19) is being explored by NovaCopper Inc. and has an indicated and inferred resource estimate of about 27 Mt of 3.3 % Cu, 4.5 % Zn, 0.8 % Pb, and 53 g/t Ag (Wilkins et al., 2013). The deposit is located between two metamorphosed rhyolite flow dome complexes (Schmidt, 1986). The orebodies consist of a number of semi-massive sulfide lenses that are up to 14-18 m thick and are situated along the limbs of an anticline within the schist belt (Newberry et al., 1997b; Wilkins et al., 2013). The main mineralized area covers about 1.3 x 1 km and extends to a depth of at least 250 m. Most of the ore appears as replacement style mineralization; stringers and stockworks are lacking (Wilkins et al., 2013). Uranium-Pb dating of syn-mineralization metarhyolites indicates ore deposition took place between 382 and 373 Ma (Ratterman et al., 2006). Geochemical data for the dated rocks and associated metabasalts suggest that the ore-forming event took place in a back-arc setting (Ratterman et al., 2006).

The ore minerals include coarse-grained chalcopyrite, sphalerite, galena, tetrahedrite-tennantite, arsenopyrite, and minor pyrite and pyrrhotite. High silver grades are associated with the tetrahedrite-tennantite. Less common ore-related phases include breithauptite, bornite, carrollite, covellite, cubanite, digenite, electrum, enargite, glaucodot, and stromeyerite (Schmidt, 1988). Schmidt (1983) described footwall Mg-rich chloritic alteration, a hangingwall pyrite-quartz assemblage, and an assemblage of phlogopite, barium-rich phengite, talc, calcite, dolomite, quartz, and barite interlayered with the sulfide horizons. Mineralization and alteration studies, as described by Schmidt (1986), in-

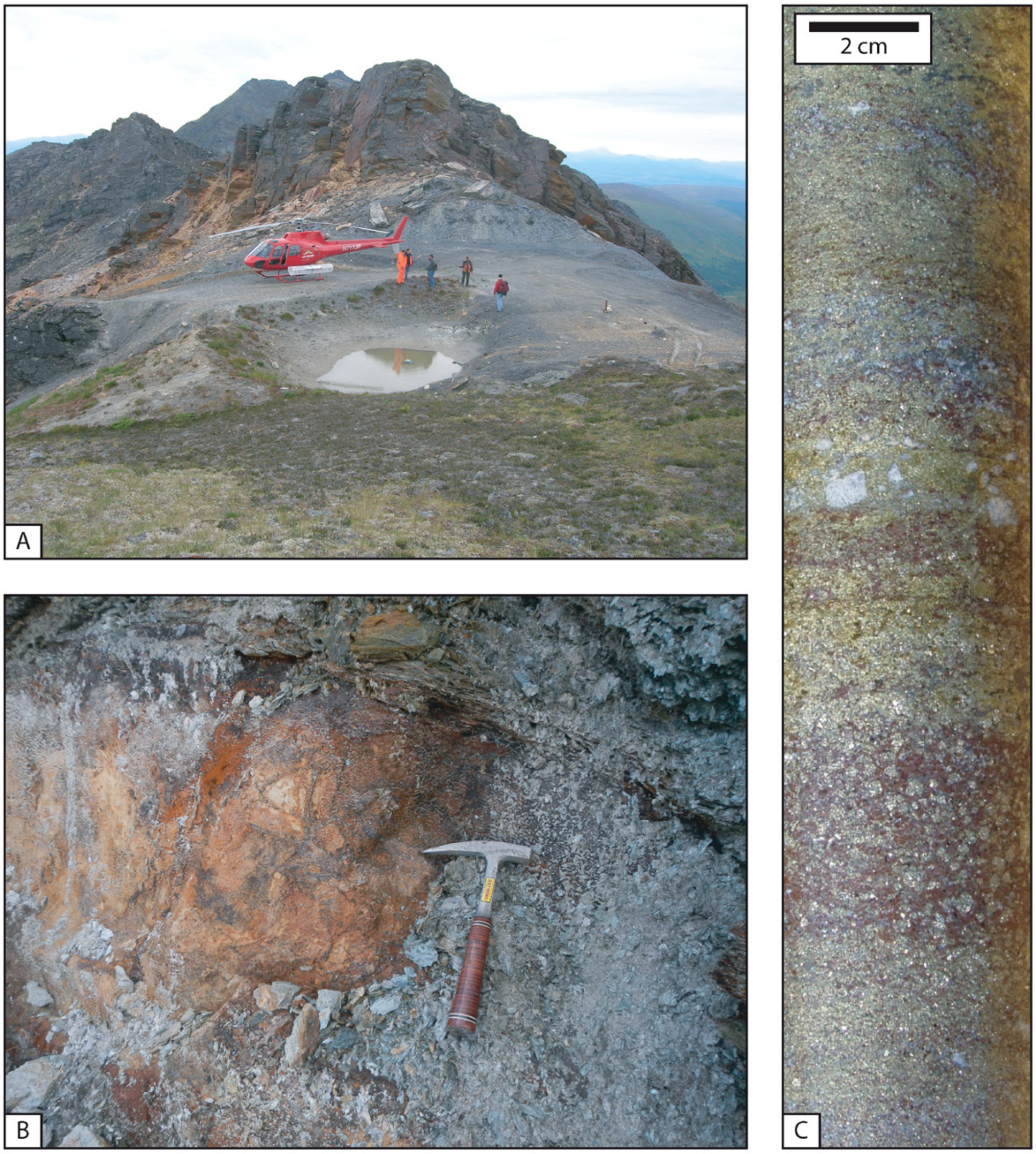


Figure 19. Site of undeveloped Arctic Cu-Zn-Ag VMS deposits in the southern Brooks Range. A) Deposit location along Arctic ridge, B) Discovery gossan on Arctic ridge with massive sulfide enclosed by talc schist. C) Mineralized drill core from Arctic ridge with abundant chalcopyrite and sphalerite. Photos courtesy of Karen D. Kelley and Garth Graham, USGS.

dicate that metals are zoned laterally from Cu-, to Zn-, and finally to Pb-Ag-rich assemblages at increasing distance from the central chloritic alteration zone. Barite gangue is specifically associated with the zinc mineralization. There is, however, no obvious vertical zoning.

Other smaller, but similar VMS occurrences within the Schist belt include Dead Creek (Shungnak) Sunshine, Horse Creek (Cliff), Sun, Tom-Tom, and Smucker (Hitzman et al, 1986; Schmidt, 1988; Newberry et al., 1997b). Most of these are Cu-Zn occurrences, but **Horse Creek** grades 9.7 % Pb and 4.1 % Zn, and only 0.5 % Cu. Gold grades for all of these smaller occurrences, as well as Arctic, range between undetectable to an average of about 1.2 g/t at the **Smucker** deposit (Newberry et al., 1997b). Silver grades locally reach 900 g/t in quartz-barite bands at **Sun** (Large). Metarhyolite samples from the **Tom-Tom** and Sun VMS occurrences in the Ambler district yielded ages similar to and slightly older than those at the Arctic deposit (McClelland et al., 2006).

Bornite carbonate-hosted copper deposit

Carbonate platform rocks exposed in a klippen a few kilometers south of the range front, host the undeveloped Bornite (or Ruby Creek) deposit (Fig. 6, Fig. 18), which is along Ruby Creek within the Ambler district (Runnels, 1969: Hitzman, 1986). The carbonate unit lies structurally above the Schist belt rocks (Till et al., 2008). The deposit is hosted in a 1000-m-thick Silurian to

Devonian marble and metadolostone sequence (Selby et al., 2009), the latter lithology perhaps of hydrothermal origin as it is highly brecciated, folded, and faulted. The breccia is syn-sedimentary and (or) hydrothermal. The lower greenschist facies carbonates are locally graphitic and phyllitic (Selby et al., 2009). Basin-margin faults appear to have localized the mineralization. Although middle Paleozoic mafic volcanic rocks and orthogneiss occur nearby, no igneous rocks are intimately associated with the Bornite deposit.

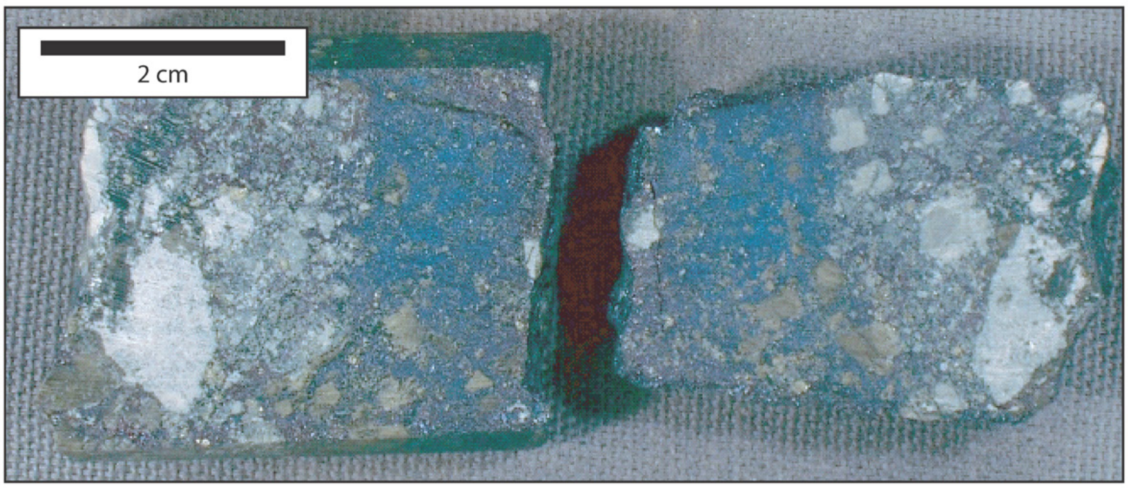
The **Bornite** deposit (Very Large), based on recent exploration by NovaCopper Inc., has an indicated open-pit resource of 14.1 Mt of 1.08 % Cu, and also an inferred resource of 109.6 Mt of 0.94 % Cu and 55.6 Mt of 2.81 % Cu for within pit and below pit ores, respectively (Davis et al., 2014), as well as highly anomalous Ag, Co, Ge, Ga, and Zn (Bernstein and Cox, 1986). Minerals associated with the copper ores include barite, bornite, carrollite, chalcocite, chalcopyrite, cymrite, galena, germanite, marcasite, pyrite, pyrrhotite, renierite, sphalerite, and tennantite-tetrahedrite. Cobalt is particularly anomalous, occurring within recrystallized pyrite rims and in carrollite (Bernstein and Cox, 1986). The ore is in stratiform zones in dolomite with stringers and veinlets, as well as the main breccia fillings. A two-stage paragenesis was described by Hitzman (1986) and Bernstein and Cox (1986). Stage 1 includes pyrite and some copper-bearing sulfides in veins, replacing matrix material in breccias (Fig. 20), and filling open-space in the dolostone. Alteration associated with stage 1 includes bleaching of phyllitic horizons, and development of hydrothermal dolomite and siderite in the limestone and phyllite, respectively. Stage 2, defining the main ore event, is characterized by copper minerals deposited in breccia matrix and in dolomite veins, with chalcopyrite replacing stage 1 massive pyrite, carrollite forming from the breakdown of cobalt-rich pyrite, and coarse-grained pyrobitumen associated with the copper minerals. The deposit is zoned from a central mineralized core of chalcopyrite, bornite, and chalcocite, outward to chalcopyrite and pyrite.

Hitzman (1986) favored ore formation at Bornite from basinal brines heated by magmatic activity, but stressed that the mineralization pre-dated the Jurassic-Cretaceous Brookian orogeny. Selby et al. (2009) dated the main stage sulfide event by Re-Os at ca. 374 Ma, an age that is similar to that of nearby VMS deposits. They identified a high Re concentration for the mineralization that was suggested to possibly reflect a role of organic matter in ore genesis. The coeval formation of VMS occurrences and the carbonate-hosted copper was suggested by Selby et al. (2009) to support the model of Hitzman et al. (1986) and Schmidt (1986) that regional extension and associated middle Paleozoic continental-margin back-arc magmatism was related to base metal deposition in the western Brooks Range. Davis et al. (2014) drew comparisons between the Bornite deposit and McArthur River (Australia), Tynagh (Ireland), Kipushi (Congo) and Tsumeb (Namibia).

Ophiolitic chromite

The allochthons of mafic and ultramafic rocks of the Angayucham terrane contain Jurassic occurrences of chromite and platinum group elements (PGE). The more than 75 occurrences contain between 3 and 15 % chromite, are as long as 600

Figure 20. Bornite mineralized carbonate breccia. Photo courtesy of Karen D. Kelley, USGS.



m, and were estimated by Foley et al. (1997) to contain between 0.64 Mt and 2.3 Mt of Cr_2O_3. The mineralization occurs in massive segregations, cumulate layers, and nodular aggregates in peridotite and dunite. Anomalous amounts of PGE are also recognized in some of the ultramafic rocks.

Deposits in the eastern Brooks Range

Economically less significant Cu, Mo, Pb, Sn, W, and Zn magmatic-hydrothermal occurrences are located in the eastern Brooks Range (e.g., Einaudi and Hitzman, 1986; Newberry et al., 1997a; Kurtak et al., 2002); none have been developed. Many of these are small Paleozoic porphyry and skarn occurrences that are overprinted and deformed during Mesozoic orogeny. Metaluminous, probably arc-related, ca. 400 Ma foliated porphyritic granite and granodiorite are cut by chalcopyrite-bearing stockworks (Newberry et al., 1986). Proximal Cu (Fig. 21A) and distal Pb-Zn skarns are associated with the porphyries where they intruded Devonian and older carbonates of the Arctic Alaska terrane (Newberry et al., 1997a). The Cu skarns (e.g., **Chandalar**) are Au-poor and contain garnet-magnetite and garnet-pyroxene-chalcopyrite assemblages. The Sn skarns (e.g., **Okpilak**) surround 380 Ma orthogneisses and are hosted by pre-Devonian carbonates. In contrast to this older mineralization, the early Tertiary **Bear Mountain** porphyry molybdenum occurrence is recognized at the eastern border of Alaska (Barker and Swainbank, 1985). Stockwork Mo-W mineralization is hosted in a breccia zone within a poorly exposed topaz-bearing rhyolite porphyry stock.

Figure 21. Mineral occurrences in the eastern Brooks Range. A) Malachite-stained skarn outcrop at Hurricane-Diane, near Roberts Creek. B) Stibnite-gold veins exposed along a faulted contact on the south side of Sukakpak Mountain. Samples contained up to 65.4 g/t gold. Photos courtesy of Joseph M. Kurtak from BLM-Alaska Technical Report 50, July 2002.

Small orogenic gold deposits are present in the Chandalar and Koyukuk districts in the southern Brooks Range. The districts historically yielded about 13.4 t of alluvial gold (Athey et al., 2014) and represent the only area across the entire Brooks Range with significant production. Placer production was greatest in the first decade of the 1900s, but working of the gravels continues today from modern stream deposits, bench placers, and older deep channels (e.g., Kurtak et al., 2002). Gold-bearing quartz veins, commonly containing abundant stibnite (Fig. 21B), have not been extensively developed and have yielded only about 0.5 t Au. The widely scattered veins fill high-angle faults and fractures that cut upper greenschist facies Devonian schist of the Arctic Alaska terrane. The ore-hosting structures likely formed during Albian regional uplift late during the Brooks Range orogeny (Dillon et al., 1987). Any genetic association with coeval Albian magmatism is, at most, indirect because the closest recognized granitic rocks of that age are 30-40 km south of the lode and placer occurrences.

Western Alaska

Orogenic gold deposits and associated placers

Small, typically poorly exposed, orogenic gold-bearing veins are widespread on the southwestern Seward Peninsula (Fig. 3; Mertie, 1918; Goldfarb et al., 1997). They mainly fill small fractures and joint sets within the calcareous metasiliceous unit of the Nome Complex, containing pure and impure marble, graphitic metasiliceous rock, pelitic schist, calc-schist, and mafic schist (Till et al., 2011, 2014). The only economic lode deposit was the **Big Hurrah** 70 km east of Nome; from 1903 to 1907, the mine produced slightly less than 1 t Au from veins in sheared metasedimentary and metavolcanic rocks, averaging 25 g/t Au (Cobb, 1978; Read and Meinert, 1986).

In 2008, a large open pit operation by NovaGold was initiated in the **Rock Creek** area (Fig. 3) about 10 km north of Nome in an attempt to produce gold from multiple veins in a bulk-tonnage type mining operation. The open pit was to have produced gold from an area with a high density of narrow sheeted quartz veins hosted by greenschist facies schist, quartzite, and marble (Otto et al., 2009), part of the calcareous siliceous unit of Till et al. (2014). The combined probable + indicated + inferred reserves were stated as 18 t Au at a 0.6 g/t cutoff, with an average grade just above 1 g/t Au. In addition, the mill at Rock Creek was planned to handle higher grade ores of 3-5 g/t to be mined by and trucked from a new open pit at the historic Big Hurrah deposit, with estimated remaining reserves of 9 t Au. However, after an initial gold pour in fall of 2008, all lode mining activities ceased due to failure of mill equipment and environmental issues.

The areas of orogenic gold veins lack known igneous intrusive rocks, although potassic granite dated between 100 and 85 Ma (Amato and Wright, 1997; Till et al., 2011) is common 40-50 km to the north and east of the gold deposits. The rocks of the Nome Complex underwent blueschist metamorphism before 120 Ma. During the Albian or early Late Cretaceous (Amato et al., 1994), rocks of the Nome Complex were overprinted by a Barrovian metamorphic event capable of producing a large volume of auriferous metamorphic fluid (e.g., Read and Meinert, 1986). Metamorphic grade locally reached upper amphibolite to granulite facies during this event (Till et al., 2011). The absence of a major, deep-crustal regional structure cutting the area affected by the mid-Cretaceous metamorphism may explain formation of hundreds of small gold-bearing veins scattered throughout the schist, rather than a small number of large tonnage ore deposits.

Ford and Snee (1996) dated hydrothermal mica at a small prospect near Nome, the Bluff occurrence, and obtained a $^{40}Ar/^{39}Ar$ age of 109.1±0.4 Ma, which was interpreted to reflect the timing of mineralization. Layer et al. (2015) dated about one dozen hydrothermal veins from the Nome district, and most measurements were Albian and almost identical to that of Ford and Snee (1996). Exceptions included the average for six dates from one sample at Big Hurrah that was 118.5±0.8, but the stepped gas release spectrum suggests a complex history and it is unclear whether any gold event was as old as Aptian, and thus older than the above described Barrovian event.

The Seward Peninsula orogenic gold province probably extends into eastern Russia, where large deposits such as Mayskoye and Karalveem are hosted by Middle Triassic sedimentary rocks and late Aptian to early Albian granite and granodiorite (Goldfarb et al., 2014). Poorly constrained ages of metamorphism and ore formation suggest a correlation of the gold event across the Bering Sea. In eastern Russia, the orogenic deposits are associated with regional anticlines in the Chukotka part of the Arctic Alaska-Chukotka microplate. Large-scale structures are better developed in Chukotka than the Seward Peninsula, which might explain the much greater lode gold favorability.

Placer gold is widespread throughout the southwestern side of the Seward Peninsula (Fig. 10A), present in alluvial, colluvial, glacial, and particularly marine strandline deposits (Cobb, 1974). Active stream channels, as well as benches with old alluvial or glacial channels high along stream walls, were productive, and in places they yielded large nuggets (e.g., Moffit, 1913). However, the majority of the recovered gold was from **beach deposits of the Nome area** (Large). The first gold discovery was on the present-day beaches of Nome, which yielded an estimated 3-4 t of Au along 60 km of coastline (Fig. 10B). Soon after this initial discovery on the "first beach", it was realized that the bulk of the gold was located slightly inland within ancient beach deposits, and these older deposits were responsible for most of the recovered 155 t Au. Six ancient beach marine platforms were located above present sea-level and an equal number were located below present sea-level (Nelson and Hopkins, 1972; Cobb, 1974). The second beach was located about 12 m above sea-level and the third beach about 26 m above. The gold within the third beach was located just above bedrock, in beach sands and river gravels at the bottom of 10-15 m deep shafts (Mertie, 1913). The most landward submarine beach was discovered 400-500 m inland and 6-7 m below present sea-level. Metz (1978) estimated reserves of 37 t Au remaining after mining, mainly in the second, third, submarine, and Monroeville beaches. Large-scale mining of the alluvial gold ceased in 1962 (Cobb, 1974), although recreational mining of many of the beaches continues today.

The marine benches formed in the late Pliocene to Pleistocene as a result of relative sea-level fluctuations. The gold-bearing gravels in the benches were deposited by glaciers on top of the schist bedrock and the fine-grained marine sediments. The gold in the till was then reworked and concentrated by both fluvial and marine processes. The latter included littoral currents and waves, bottom currents, and shoreline migration (Kaufman and Hopkins, 1989). Offshore alluvial gold occurrences are also abundant for about 15 km in length parallel to the present beach at Nome, for distances of about 5 km outward into the Bering Sea and to depths of 20 m (Nelson and Hopkins, 1972; Kaufman and Hopkins, 1989). The greatest concentration of gold is in the upper 4 m of seafloor sediment. These concentrations were also products of Pleistocene glaciation that carried eroded lode, alluvial, and beach placers offshore. Nelson and Hopkins (1972) indicated the offshore lag gravels contained, on average, eight times the amount of gold as the parent tills. During a 4-year period beginning in 1987, WestGold used an offshore dredge to recover slightly more than 3 t Au. Bronston (1992) estimated nine deposits with a remaining offshore resource of 18 t Au at a grade of 1020 mg/m^3.

Lode and placer tin deposits

The northwestern part of the Seward Peninsula hosts a 170-km-long belt of Late Cretaceous granite-related tin deposits (Fig. 3) occurring as magmatic veins, greisens, skarns, and placers (Fig. 18; Knopf, 1908). Where there has been little erosion and plutons are buried or only poorly exposed, important lode resources may exist, whereas if plutons have been deeply eroded and widely exposed, most of the tin is in alluvial deposits (Swanson et al., 1990). Early seriate and porphyritic biotite granites formed idiocrase-scapolite-diopside skarns in limestone that were metal-poor. Shallower and later equigranular biotite granite formed pyroxene-garnet-tourmaline-cassiterite skarns, as well as tin-rich greisen (Swanson et al., 1990). The deposits are consistently enriched in B, Be, F, and W. The belt may be continuous into adjacent parts of eastern Russia (e.g., Alexsandrov, 2010).

The **Lost River** tin skarn deposit in the York Mountains, about 135 km northwest of Nome, produced 314 t Sn in the first half of the 1950s (Lorain et al., 1958) and is the largest historic tin producer in Alaska. The mineralization is mostly adjacent to the buried cupola of one of a series of ca. 80 Ma evolved granite intrusions in the western Seward Peninsula that intrude Early Ordovician limestone. Four stages of hydrothermal activity have been described (Dobson, 1982; Hudson and Reed, 1997; Newberry et al., 1997a). Initial Mg-Al-Fe-rich skarn formation included some tin enrichment in silicate phases, such as garnet and idocrase. An overprinting hydrous skarn-forming event included deposition of cassiterite, as well as pyrite, pyrrhotite, chalcopyrite, sphalerite, scheelite, fluorite, tourmaline, biotite, and hornblende. The tin-rich mineralization is associated with greisenization along the margin of the intrusion. This was followed by formation of post-skarn fluorite-white mica veins, and then solution breccias that overprinted and oxidized many of the ore minerals and deposited fluorite and kaolinite. Each stage may have further concentrated the tin and upgraded the ore deposit (Dobson, 1982).

The past production at Lost River, from ore that averaged 1.42 % Sn, was from the so-called Cassiterite Dike, which occurs as a muscovite-quartz-tourmaline-topaz roof greisen replacing quartz porphyry dikes and limestone at the top of the buried intrusion (Sainsbury, 1964, 1988; Hudson and Reed, 1997). The greisen is as much as 30-60 % muscovite (Dobson, 1982). The greisenization resulted in deposition of cassiterite and sulfide minerals within the altered dikes that have a maximum width of about 6 m. The metallic minerals are disseminated and in crosscutting veins in the greisen. A clay alteration overprint has commonly broken down all mineral grains except for the cassiterite. Zoning of

Figure 22. A) Folded sulfide-magnetite-fluorite-carbonate lens in marble, Wheeler North deposit. B) Folded barite-carbonate rock (exhalite), Aurora Creek deposit. Photos courtesy of John F. Slack.

a beryllium-rich assemblage, including fluorite, chrysoberyl, beryllium diaspore, white mica, tourmaline, and minor beryl, euclase, bertrandite, and phenacite is noted both outward and upward from the cassiterite-rich assemblage. Reported resource estimates for the tin skarn are approximately 55,000 t Sn from ore with an average grade of 0.26 % Sn (Hudson and Reed, 1997).

The other major lode tin deposit is the undeveloped **Kougarok** deposit, with estimated reserves of 90,000 t Sn. The deposit was discovered based on a stream sediment survey in the late 1970s (Puchner, 1986). The cassiterite is associated with zinnwaldite and muscovite in a greisenized late stage granite, similar to Lost River. Relatively less abundant cassiterite is associated with disseminations and stringers of tourmaline, axinite, chlorite, and quartz in altered schist country rocks.

Almost all of the tin mined in Alaska has been from placer occurrences of the Seward Peninsula, particularly along **Cape Creek** draining Cape Mountain (Fig. 3; 1676 t Sn) and from Buck Creek and upper tributaries to the Anikovik Rover near Potato Mountain (1000 t Sn). Production was discontinuous between 1911 and 1990 (Hudson and Reed, 1997). The alluvial tin in these areas is sourced from the erosion of upstream cassiterite-bearing quartz veins and skarns in deeply eroded granites (e.g., Swanson et al., 1990). Hudson and Reed (1997) indicate the favorable pay streaks may reach a few kilometers in maximum length, are as much as 100 m in width, and have variable thickness to a maximum of a few tens of meters.

Other deposit types of the Seward Peninsula

Metacarbonate and metaclastic rocks of the Nome Complex in the southern half of the Seward Peninsula also host small, but widespread deformed and metamorphosed Zn-Pb±Ag deposits and occurrences (Fig. 3; Slack et al., 2014). They occur predominantly in the same rocks and over much of the same area as the orogenic gold deposits, and have no spatially associated igneous rocks. In contrast to the Cretaceous gold deposits, however, these base metal deposits (e.g., **Aurora Creek, Galena, Nelson, Quarry, Wheeler North**) are present as pre-Carboniferous sub-seafloor replacement (clastic-dominated Pb-Zn) deposits (Fig. 22) that have had only sporadic, small-scale development. The sphalerite, galena, and pyrite ores occur as lenses of disseminated to semi-massive sulfide, within quartz, siderite, and ankerite gangue, and have local concentrations of barite and fluorite. Slack et al. (2014) pointed out that sphalerite aligned in foliations and folded barite bodies are consistent with deformation of the occurrences during the Brooks Range orogeny.

A second group of Zn-Pb-Ag occurrences (e.g., **Hannum, Independence, Omilak, Foster**) is located in central Seward Peninsula near the Cretaceous intrusions in amphibolite facies rocks of the Nome Group. The sulfides occur as disseminations, and in veins, pods, and stringers that replace the schists and marble and are present along the contacts between the units. Because the occurrences appear undeformed and unmetamorphosed, and have very high $^{206}Pb/^{204}Pb$ ratios (Ayuso et al., 2014), they are ap-

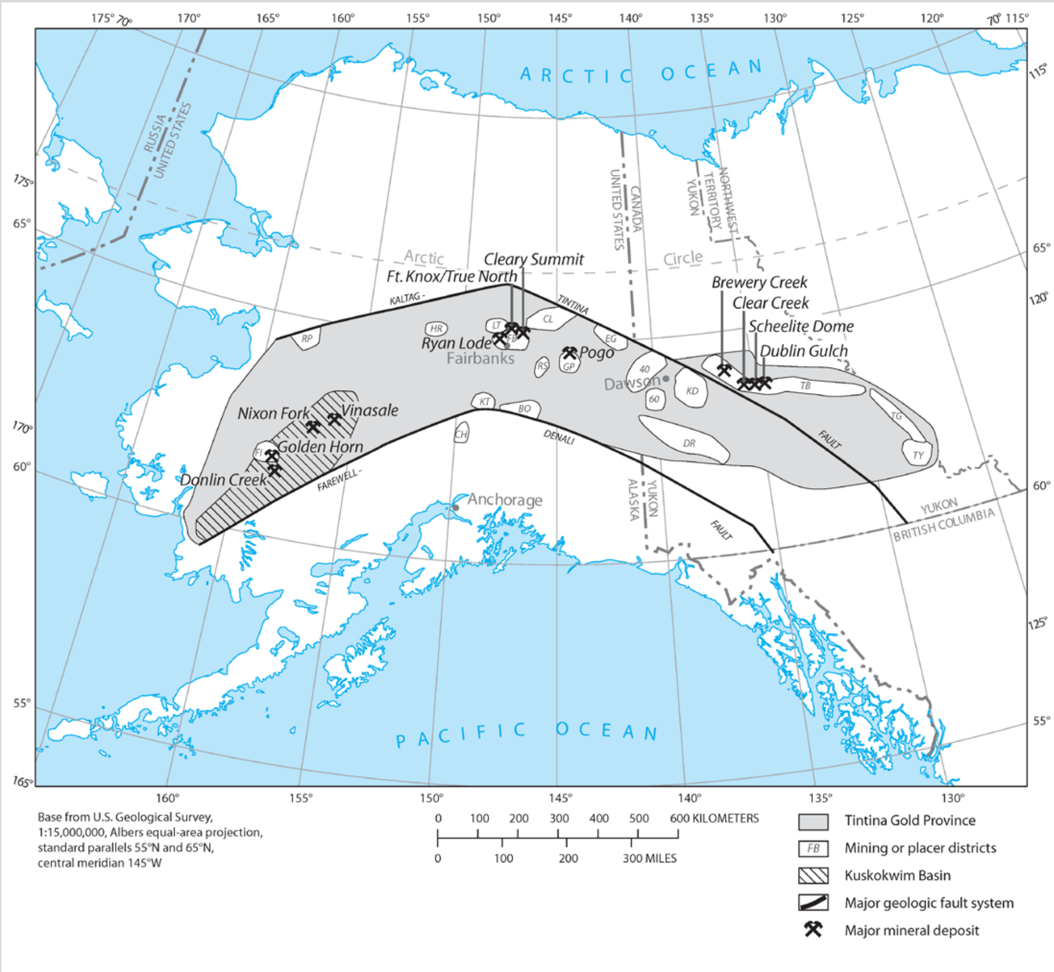


Figure 23. Major middle to Late Cretaceous gold-bearing lode deposits of the Tintina Gold Province of interior Alaska and adjacent Yukon, Canada. The districts are all known for their historic placer gold production, but many areas, notably the Kuskokwim, Fairbanks, Goodpaster, and Tombstone regions, 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 [or Tolovana]; RP, Ruby-Poorman; RS, Richardson; TB, Tombstone; TG, Tungsten; TY, Tay River (after Hart and others, 2002).

parently no older than Cretaceous. Furthermore, the spatial association with the granitic rocks hints at a genetic association.

The **Boulder Creek** or Death Valley uranium deposit in eastern Seward Peninsula (Fig. 3), described by Dickinson et al. (1987), is the northernmost sandstone-type uranium deposit identified in the world. Discovered in 1977, it is hosted in early Eocene continental arkosic and conglomeritic sedimentary rocks that unconformably overlie a weathered Cretaceous granite. The mineralization is about 100 m thick and consists of coffinite and minor pyrite; in places of supergene enrichment, the uranium minerals have been converted to meta-autunite. The Boulder Creek deposit is estimated to contain 453 t U_3O_8 with an average grade of 0.27 % U_3O_8; the deposit has been explored, but not developed. The deposit formed when uranium was leached from the weathered granite by oxidized groundwater and deposited at a redox front represented by carbonaceous matter and coal within clastic sediments. A much more temperate or subtropical climate would have been required in the early Eocene to form such a deposit.

Ruby geanticline

Southeast of the Seward Peninsula, the relatively isolated **Illinois Creek** polymetallic vein deposit formed along the southwestern side of the Ruby Geanticline (Ruby terrane of figure 6), a regional NE-trending uplift of mainly early Paleozoic metasedimentary rocks of mainly continental-margin affinity in interior Alaska. Patton et al. (1994) correlated these rocks with those of the southern Brooks Range, although their history remains unclear (e.g., Bradley et al., 2007). The Illinois Creek deposit (located in Ruby-Poorman district; see below figure 23), discovered in the Kaiyuh Hills in 1980, was mined from a seasonal open-pit heap leach operation between 1997 and 2004, producing about 5 t Au and 24 t Ag from ore averaging 2 g/t Au and 43 g/t Ag. At least equal amounts of ore remained but mining ceased due to financial and environmental issues. The mined out oxide ore was hosted in a shear zone that extends for at least 2 km within a pelitic schist; the nearest intrusion is 12 km to the north of the deposit (Flannigan, 1998). Gold occurs in oxidized pyrite grains within Fe-stained vein quartz, but at depth it occurs with numerous polymetallic sulfides and sulfosalt minerals. The ca. 113 Ma age for both the Illinois Creek deposit and the granite to the north led Flannigan (1998) to classify the deposit as an intrusion-related vein system. Recent exploration in the area has focused on polymetallic replacement and porphyry copper potential, but this part of west-central Alaska is extremely remote and much of the area is under cover so the resource potential of the Ruby Geanticline remains unclear.

Metallogeny of the Farewell terrane

The Farewell terrane (Fig. 4), connected with Arctic Alaska terrane into the Devonian, has resource favorability for deposits similar to those of the southwestern part of the Brooks Range. Schmidt (1997) suggested that some of the early to middle Paleozoic rocks of the Farewell terrane have potential for undiscovered clastic-dominated Pb-Zn and barite deposits. The **Reef Ridge** zinc deposit (420,000 t grading 17.4 % Zn; Fig. 4), as well as other nearby smaller occurrences, are hosted by Early to Middle Devonian shallow water platform dolomite. They are dominated by smithsonite that formed during cold, humid weathering of sphalerite and carbonates in the late Tertiary and Holocene (Santoro et al., 2015). The precursor sulfide ores were interpreted as Mississippi Valley-type deposits by Schmidt (1997). However, as pointed out by Santoro et al. (2015), a spatial association with Late Cretaceous porphyry prospects and the Nixon Fork Cu-Au skarn to the southwest (see below discussion of SW Alaska) suggests the Reef Ridge deposit and related Zn-nonsulfide replacement and veinlet occurrences formed from supergene alteration of Late Cretaceous magmatic hydrothermal vein deposits. In addition, in many parts of the Farewell terrane there are relatively unexplored occurrences of barite and phosphates (Bundtzen and Gilbert, 1991; Dumoulin, 2015).

Eastern interior Alaska

Gold metallogeny

Eastern interior Alaska contains significant gold resources in orogenic gold deposits, a world-class intrusion-related gold deposit, and widespread alluvial deposits. The deposits define a part of what has become widely known to explorationists as the Tintina Gold Belt or Tintina Gold Province (Fig. 23), which extends for >1500 km from southwestern Alaska, through central and eastern Alaska, and into western Yukon (e.g., Goldfarb et al., 2000; Tucker and Smith, 2000). The belt, however, consists of many different gold deposit types of various ages and therefore the term Tintina Gold Belt is more of a promotional term, lacking scientific merit, rather than one reflecting a well-defined belt of related auriferous ore deposits.

In the Fairbanks district, the approximately 300 t Au **Fort Knox** deposit (Very Large) (Fig. 24A) is perhaps the only global example of an economic reduced intrusion-related gold system; the term “system” is used by many workers due to zoning of deposit types around a causative intrusion (e.g., Hart et al., 2002). These systems were first described as including potential economic gold deposits by Thompson et al. (1999), Thompson and Newberry (2000), and Lang et al. (2000). This model was predominantly based upon the Fort Knox deposit in Alaska, and similar prospects, such as Scheelite Dome, Dublin Gulch, and Clear Creek (Fig. 23), in adjacent Yukon. Prior to the development of the reduced intrusion-related gold system model, similar magmatic and mineralogic features had previously been described for gold skarns related to reduced intrusions (Meinert, 1989; 1995).

The Fort Knox deposit, about 25 km northeast of the city of Fairbanks, is located in the apex of the variably porphyritic, moderately reduced, monzogranite to granodiorite Vogt stock (Bakke, 1995). The 92.5 Ma host stock, which intrudes the Proterozoic to middle Paleozoic Fairbanks schist, is characterized by a low magnetic susceptibility and an Fe_2O_3/FeO ratio of 0.15-0.30 (Hart et al., 2004a). The stock had a pre-mining surface exposure of 1100 x 600 m. Bakke (1995) subdivided the stock into an early biotite-rich fine-grained granite, a medium-grained porphyritic granite, and a youngest coarse-grained seriate porphyritic granite. Isotopic data from the ore-hosting stock at Fort Knox indicate a magma origin reflecting both mantle and crustal contributions (Haynes and et al., 2005).

The gold occurs in steeply-dipping, commonly sheeted, quartz-K-feldspar veins, and in planar quartz veins that occur along later gently- to moderately-dipping shear zones cutting the igneous rocks (Fig. 24B-C). The sheeted veins have been referred to as pegmatites by some workers, but are definitely veins with clear to gray quartz and K-feldspar grains that were deposited by a hydrothermal fluid. The density of the sheeted veins strongly controls the ore grade. The veins generally fill northwest-striking, shallowly to moderately southwest dipping shear zones, and individual veins range in width from 0.3-1.5 m. Some of the veining also may appear as thin quartz stockworks. High fineness gold in the veins is commonly intergrown with native bismuth, bismuthinite, and tellurobismuth (McCoy et al., 1997). Total sulfide volume is typically much less than 1 % and bismuthinite is commonly the most abundant sulfide phase in the veins. Other minor sulfides include pyrite, pyrrhotite, arsenopyrite, and molybdenite; traces of scheelite are also present. Alteration phases include K-feldspar, albite, biotite, sericite, and ankerite; they generally define haloes surrounding veins of only a few centimeters (Fig. 24B). A Re-Os date on hydrothermal molybdenite of 92.4±1.2 Ma is identical to the crystallization age of the Fort Knox stock (Selby et al., 2002).

A set of late, through-going, northeast-trending shear veins cut the stock and sheeted veins (Fig. 24D). Their structural evolution has not been well studied, but they are important in adding grade to the total resource and increasing the overall grade of the historically recovered ores

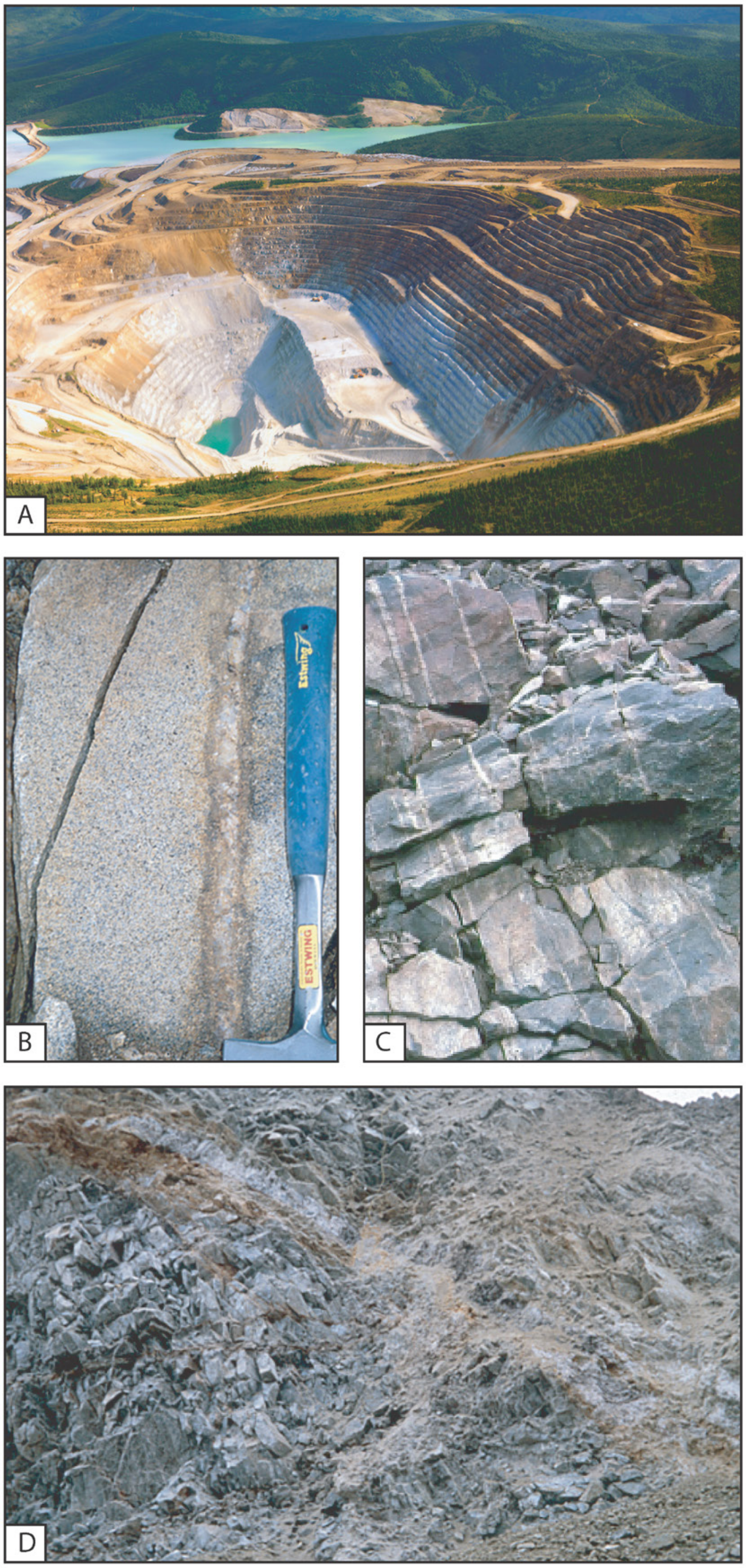
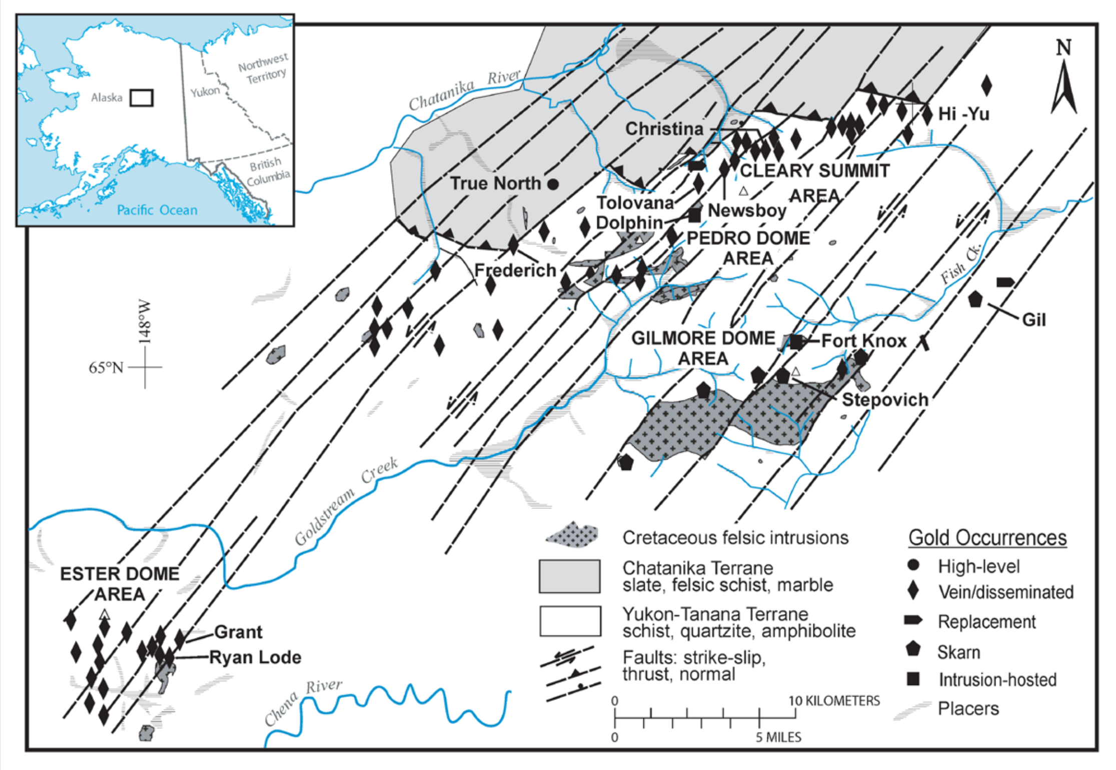


Figure 24. Fort Knox is the largest lode gold producer in Alaska and is the one example of a productive reduced intrusion-related gold system as defined by Lang et al. (2000) and Hart et al. (2002). A) The Fort Knox pit near Fairbanks, Alaska has yielded 300 t Au from the cupola of a reduced stock (photo from Paul Andrew Lawrence). B, C) Most gold at Fort Knox has been recovered from low-grade sheeted quartz-K-feldspar veins with few sulfides and narrow alteration haloes. D) Late NE-trending shears, about 0.5 m in width, cut the host stock and typically contain highest-grade ores.

Figure 25. Gold deposits of the Fairbanks district, east-central Alaska. Most are small orogenic gold deposits that are associated with a northeast-striking system of faults and were the source for the large placer endowment of the district. In addition, the giant Fort Knox intrusion-related gold system and nearby small skarns occur in the Gilmore Dome area.



to about 0.9 g/t Au (Arne Bakke, oral commun., 2003). It is likely that if it were not for these auriferous late shears, the Fort Knox gold deposit would not have been economic.

Numerous smaller gold deposits are also distributed throughout the Fairbanks district (Fig. 25; Goldfarb et al., 1997; McCoy et al., 1997, Bakke et al., 2000; Hart et al., 2002). The **True North** deposit (4.7 t Au produced), originally prospected 100 years earlier as an antimony prospect, was briefly mined for gold, providing higher-grade feed for the Fort Knox mill, from 2001-2005. This deposit, located about 20 km northwest of Fort Knox, is comprised of 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. Igneous 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 or stibnite, occur throughout the district. The largest, the **Ryan Lode** (Medium) (<1 t Au produced), occurs along the sheared margin of a tonalite stock. The majority of the schist-hosted deposits (e.g., Grant, Cleary Hill, Newsboy, Hi-Yu, Christina, Tolvana) are along steeply-dipping, NE- or NW-trending fault zones and have characteristic quartz-sericite-ankerite alteration haloes. ^{40}Argon/^{39}Ar hydrothermal mica dates of 103 Ma for the Hi-Yu deposit (Goldfarb, unpub. data) and 89 Ma for the Ryan Lode (McCoy et al., 1997), as well as a Re-Os sulfide date of 92 Ma for Tolovana (Goldfarb, unpub. data), suggest that the schist-hosted deposits both overlap and pre-date Cretaceous magmatism in the district. Many of these deposits hosted in the Fairbanks Schist are best classified as orogenic gold deposits, although the Gil deposit may be similar to Fort Knox in having a close association with magmatic-hydrothermal activity.

Erosion of the widespread auriferous quartz veins has yielded alluvial concentrations responsible for 257 t Au production from **placers of the Fairbanks district** (Very Large) (Fig. 11). Production peaked during the first few years of mining after discovery of alluvial concentrations in 1902 and during a lengthy period of dredging between 1928 and 1963. Most production came from the watersheds of Cleary, Fairbanks, Ester, Dome, and Goldstream Creeks. The most productive pay streaks were typically less than 100 m in width and at or near the bedrock contacts (Tuck, 1968). The late Pliocene to middle Pleistocene Cripple and Fox Gravels were most productive (Pewe, 1975). Metz (1991) suggested the most important placers formed in streams forming a barbed drainage pattern, where tributaries flow in the opposite direction to their master streams and thus join these streams in a hook-shaped bend. Such drainages developed in areas of basement structures, where channels were captured and altered by the basement features.

The Goodpaster mining district, located about 140 km southeast of Fairbanks (Fig. 23), was characterized by only very minor gold production from small vein and placer occurrences for 100 years. However, high-grade (avg. 12.5 g/t Au), shear-hosted veins cutting Proterozoic to middle Paleozoic biotite-quartz-feldspar orthogneiss and paragneiss of the Yukon-Tanana terrane (Day et al., 2003) were discovered at **Pogo** (Large) in 1996. Underground mining began ten years later. As of 2015, Pogo is the largest gold producing mine in Alaska, producing about 11 t Au/year and with a present production, reserve, and resource total of 220 t Au.

The gold-bearing veins at Pogo, termed the Liese vein system (Fig. 26), occur as three individual, laminated, stacked veins that dip shallowly to the northwest. The ductile to brittle veins average 7 m in thickness, although they are locally as thick as 30 m, and have an aerial extent of 1.4 x 0.7 km (Smith et al., 1999; Rhys et al., 2003). The largest vein has a down-dip extent of >1.7 km. The dominant foliation and stretching lineations at the Pogo deposit are interpreted to be consistent with a regional compressive regime forming the main flat veins and a switchover to extensional stresses to form steeper brittle tensional veins that are also gold-bearing (Eric Jensen, University of Alaska-Fairbanks, written commun., 2009). Sulfide phases, comprising about 3 % of the veins, include arsenopyrite, pyrite, pyrrhotite, loellingite, chalcopyrite, and molybdenite; Bi- and Te-bearing tellurides are also present. Alteration phases include biotite, quartz, sericite, K-feldspar, ferroan dolomite, and chlorite.

Reduced granites and tonalites of the Goodpaster batholith are located a few kilometers north of Pogo. These rocks were intruded ca. 109-103 Ma, during the final stages of regional metamorphism and deformation (Dilworth et al., 2007). In contrast to those associated with the Fort Knox deposit that have a significant mantle component, the magmas that formed the Goodpaster batholith are mainly crustal melts. Igneous activity overlaps with the 104.2 Ma mineralization age as determined by Re-Os analysis of ore-related molybdenite (Selby et al., 2002). The deposit is cut by a post-kinematic 94 Ma diorite. The

Figure 26. Other historic placer gold districts of east-central Alaska have been the sites of recent important lode discoveries. The Pogo orogenic gold deposit in the Goodpaster district, discovered in 1996, is now the largest annual gold producer in Alaska, yielding about 11 t Au per year.

temporal association of the intrusions with the gold event has led most workers to define Pogo as an intrusion-related gold system. However, many features of the deposit suggest that it is no different than most orogenic gold deposits and a genetic relationship to magmatism is far from conclusive (Goldfarb et al., 2000, 2005).

The Tolovana mining district is located 75 km northwest of Fairbanks (Fig. 23). It has yielded about 16 t of placer gold in the past 100 years, and significant alluvial resources are still present. Small sulfide- and gold-bearing quartz veins in Paleozoic schist, volcanic rocks, and ultramafic rocks have been prospected on **Money Knob**, a domal feature in the headwaters of many of the gold-bearing creeks. A bulk minable target was defined in the area of the Money Knob prospects in 2007, namely the **Livengood deposit** (Very Large), with present measured, indicated, and inferred resource estimates of about 570 t Au at an 0.3 g/t Au cutoff and averaging just above 0.5 g/t Au (International Tower Hill website).

There is little detailed information on the Livengood deposit, with the only published geology in Pontius et al. (2010). The mineralization seems to be within a complex series of fault slices of Cambrian mafic and ultramafic rocks and Devonian clastic and volcanic rocks, with most ore in the latter sequence. The mineralization at Money Knob is both disseminated and vein-hosted. Arsenopyrite, pyrite, and lesser stibnite are commonly associated with the gold. Alteration phases are dominantly biotite, sericite, and albite, although a silica-carbonate-talc assemblage is reported in the ultramafic rocks. Mid-Cretaceous stocks, dikes, and sills are widespread in the area of Money Knob, leading most reports on the deposit to define it as an intrusion-related gold system, although descriptions of some of the mineralization styles on the dome also are consistent with an orogenic gold deposit classification. The lack of anomalous Bi and Te was argued by Pontius et al. (2010) to indicate that Money Knob was a "distal" intrusion-related gold system.

Important lode gold deposits have yet to be discovered in other placer mining districts of east-central Alaska, such as **Circle**, **Rampart**, **Fortymile**, and **Hot Springs**. Yeend (1991) noted that in the Circle district, alluvial gold was mainly concentrated in the lower 1 m of stream gravels and the underlying upper 0.5 m of bed-

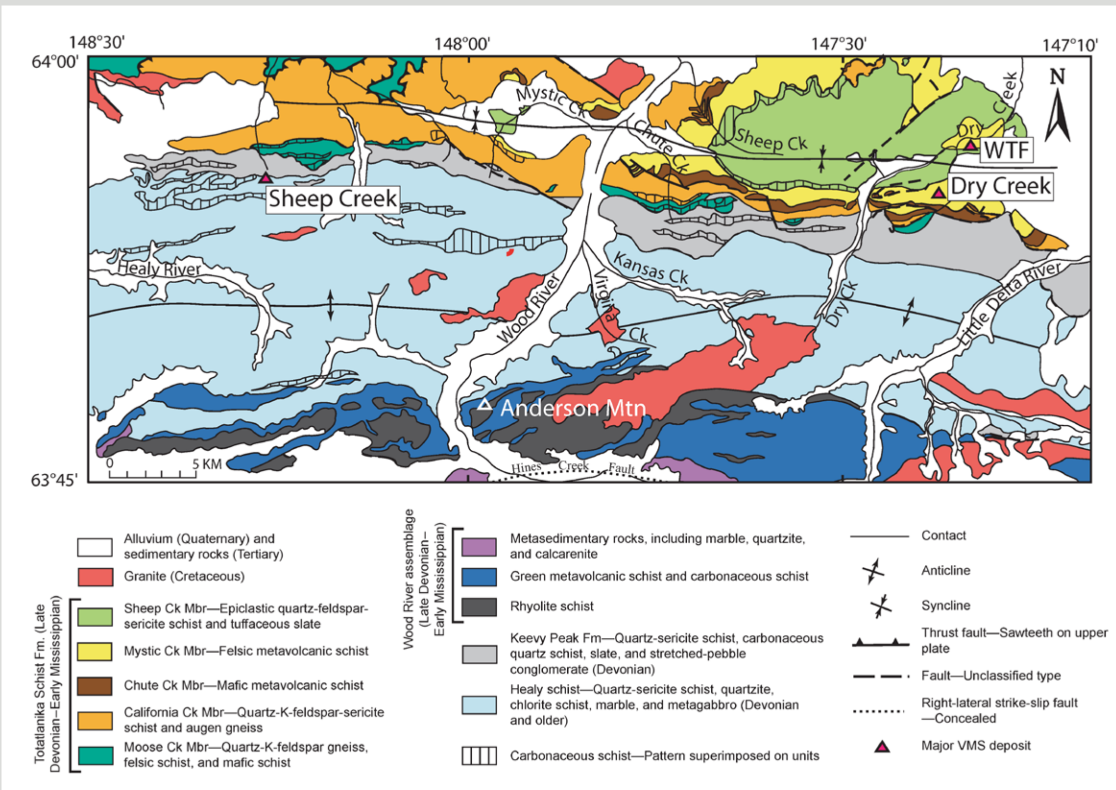


Figure 27. Geologic map showing location of the major VMS deposits, such as Dry Creek and WTF deposits, of the Bonnifield district, east-central Alaska. Modified after Dusel-Bacon et al. 2012.

rock. A strong correlation of gold-rich channels with mafic schist was observed, but significant lode sources have not been located in more than 100 years of prospecting in the district. Similarly, in the Fortymile district, the gravel-bedrock interface has localized most of the recovered alluvial gold (Yeend, 1996). It remains uncertain as to whether (1) all gold-bearing lodes are small and scattered, (2) most lode endowment has been lost to erosion, and (or) (3) future lode discoveries, such as in the Fairbanks, Tolovana, and Goodpaster districts, are still possible in these other historic placer districts. Allan et al. (2013) have noted that a few small gold-bearing veins in the Fortymile district could have formed at any time from Middle Jurassic to early Tertiary, so therefore even the ages of potential source lodes for the alluvial gold are not clear.

Volcanogenic massive sulfide deposits

Polymetallic VMS deposits of the Bonnifield and Delta districts are located along the north side of the Denali fault system in the northern foothills of the eastern Alaska Range (Fig. 6). The deposits are part of a series of Zn-Pb-Ag-Au±Cu massive sulfides formed during back-arc extension and the Devonian-Mississippian opening of the Slide Mountain Ocean (Nelson et al., 2013). Tertiary dextral displacement has resulted in wide distribution of these deposits in western Canada and eastern Alaska. The northernmost deposits hosted in the parautochthonous rocks of Yukon-Tanana terrane (e.g., Bonnifield and Delta districts) have had no development.

The Bonnifield district, about 80 km south of Fairbanks, hosts 26 siliclastic-felsic type VMS occurrences in peralkaline metarhyolite and intercalated graphitic and siliceous argillite of the Totatlanika Schist (Fig. 27; Dusel-Bacon et al., 2012). The ca. 373-356 Ma mineralization is primarily pyrite and sphalerite, with lesser galena, tetrahedrite, and chalcopyrite (Fig. 28). High-grade zones of sulfide minerals are locally as thick as 13 m. The largest reported resource is for the combined **Dry Creek** (Red Mountain) and **WTF** deposits, with 5.7 Mt at 4.4-6 % Zn, 2.5 % Pb, 0.3 % Cu, 94-179 g/t Ag, and 0.5-0.9 g/t Au. The massive sulfide bodies have been overprinted by Mesozoic deformation and greenschist facies metamorphism. Similar mineralization of the same age, although with smaller recognized resources, is characteristic of the Delta

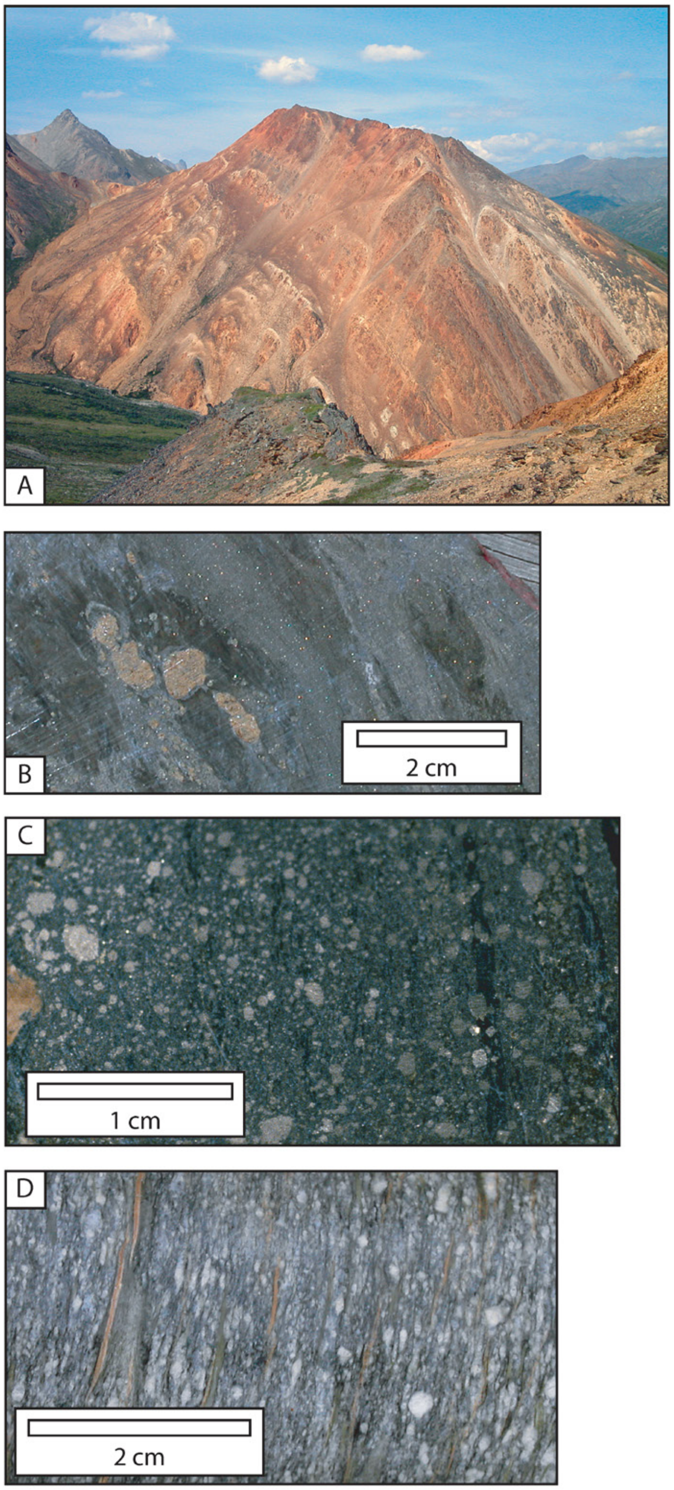
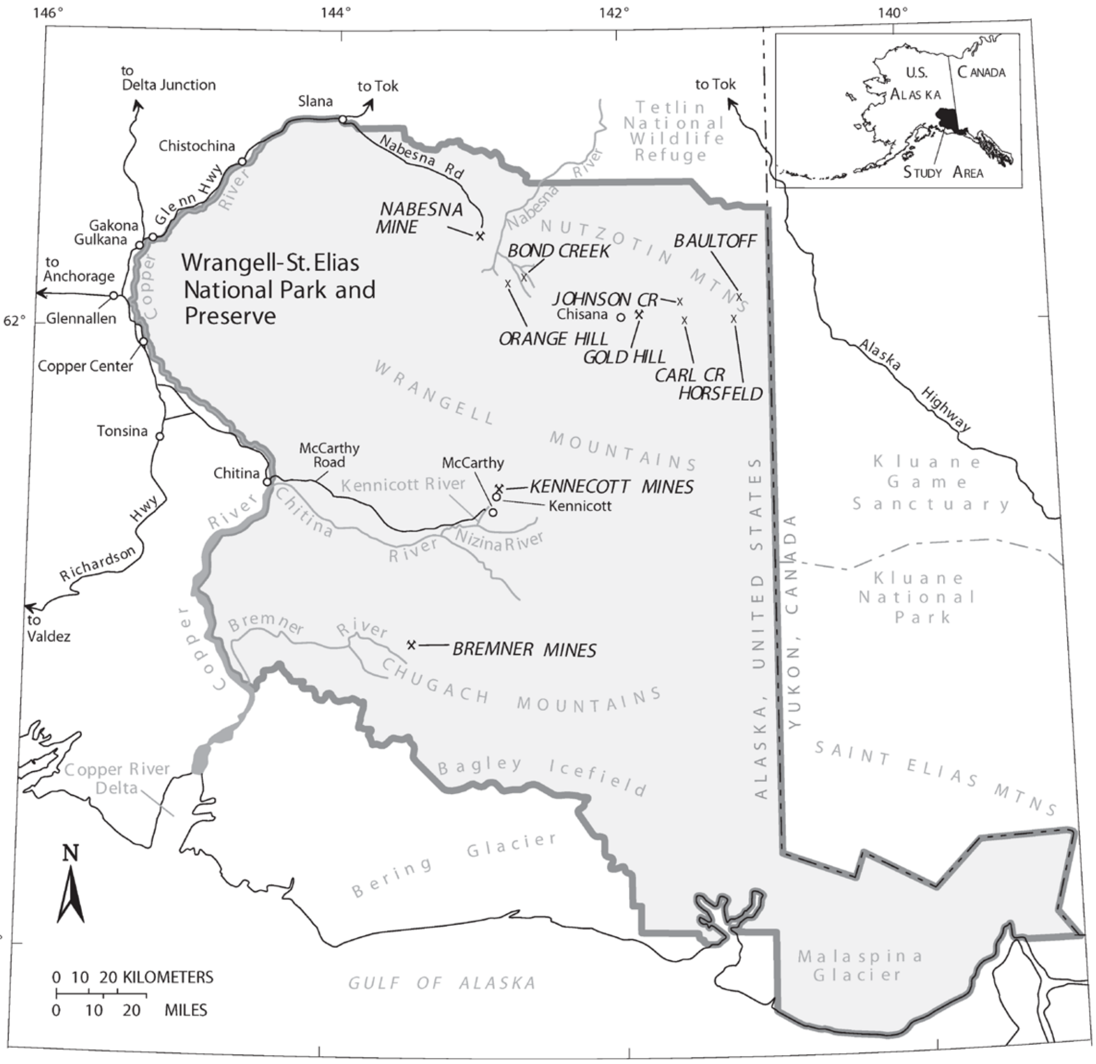


Figure 28. Major deposits of the Bonnifield VMS district. A) Dry Creek (Red Mountain) showing N-dipping quartz-sericite-pyrite-altered felsic metavolcanic rocks and carbonaceous phyllite (looking northwest). B) Phyllitic mudstone with disseminated pyrite and beige sphalerite, with several ovoid clots of salmon-colored sphalerite (Foster Creek Zone, Red Mountain deposit). C) Semi-massive sulfide with subrounded grains of pyrite, laminar sphalerite, and minor chalcopyrite and galena (DC south Zone, Red Mountain deposit). D) Quartz-K-feldspar-phyric metarhyolite with disseminated pyrite, and discontinuous bands of Fe carbonate and minor sericite (WTF deposit). Photos courtesy of Cynthia Dusel-Bacon.

Figure 29. Location of unmined porphyry copper deposits and Nabesna skarn in the eastern Alaska Range and Kennecott-type copper deposits in the Wrangell Mountains of eastern Alaska. The deposits are closed to mine or exploration activity within the boundaries of Wrangell-St. Elias National Park and Preserve. Modified after Eppinger et al., 2000.



district about 150 km southeast of the Bonnifield deposits (Fig. 6; Dashevsky et al., 2003). Globally, such VMS occurrences associated with alkalic magmatism have to a large degree proven to be uneconomic (Jim Franklin, oral commun., 2015).

Porphyry copper deposits

A number of porphyry copper deposits are located within the high elevations of the eastern Alaska Range (Fig. 5, 29, 30A-C) to the south of the Denali fault system, but their remoteness and low metal grades has long discouraged development. Intrusions hosting the Cu±Mo-Au stockworks and disseminations (Fig. 30D-F) were emplaced at ca. 117-105 Ma and are exposed over an area of about 250-300 km^2 (Richter 1976). They intrude late Paleozoic to Triassic metasedimentary and metavolcanic rocks of the Wrangellia composite terrane close to its landward contact with the Jurassic-Cretaceous flysch of the Nutzotin basin. The porphyry deposits probably formed along what was then the continental margin, more than 1,000 km south of their present-day latitude, during the cessation of basin sedimentation and the onset of a continental margin transpressional regime (Fig. 31). The giant Pebble porphyry deposit in southwestern Alaska (see below) may be part of the same middle Cretaceous post-subduction magmatic-hydrothermal episode (Goldfarb et al., 2013).

The mineralized intrusions in the eastern Alaska Range were estimated to cumulatively contain about 1,000 Mt averaging 0.25-0.35 % Cu (Richter et al., 1975). The Klein Creek pluton consists of granodiorite, monzonite, and diorite and hosts the Baultoff, Carl Creek, and Horsfeld deposits along the Alaska-Yukon boundary. About 50 km to the southwest, the major part of the inferred resource is present in the Orange Hill and Bond Creek deposits that are hosted in the granodiorite and quartz diorite of the Nebesna batholith. The **Orange Hill** deposit (Very Large)

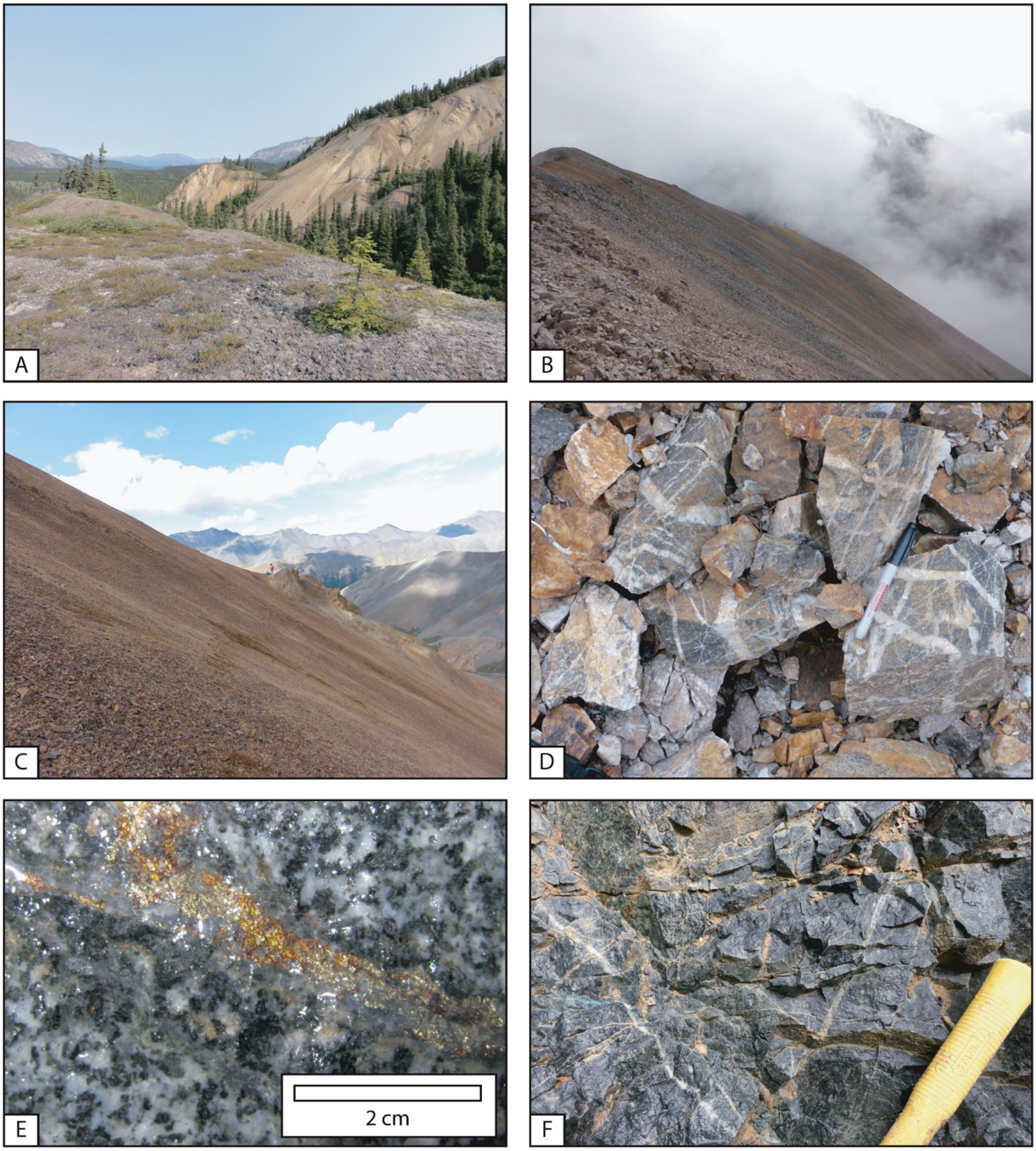


Figure 30. Copper porphyry occurrences in the eastern Alaska Range. A) View on top of Orange Hill porphyry looking N to NNE. B) Bond Creek Ridge, site of Bond Creek porphyry. C) Pyritic talus slope at the Baultoff deposit. D) Low-grade stockwork veining in the Orange Hill intrusive in the upper reaches of California Gulch. E) Drill core showing quartz-chalcopyrite vein from Orange Hill. F) Stockwork quartz-chalcopyrite veining in heavily altered volcanic rocks, Bond Creek. Photos courtesy of Garth Graham USGS.

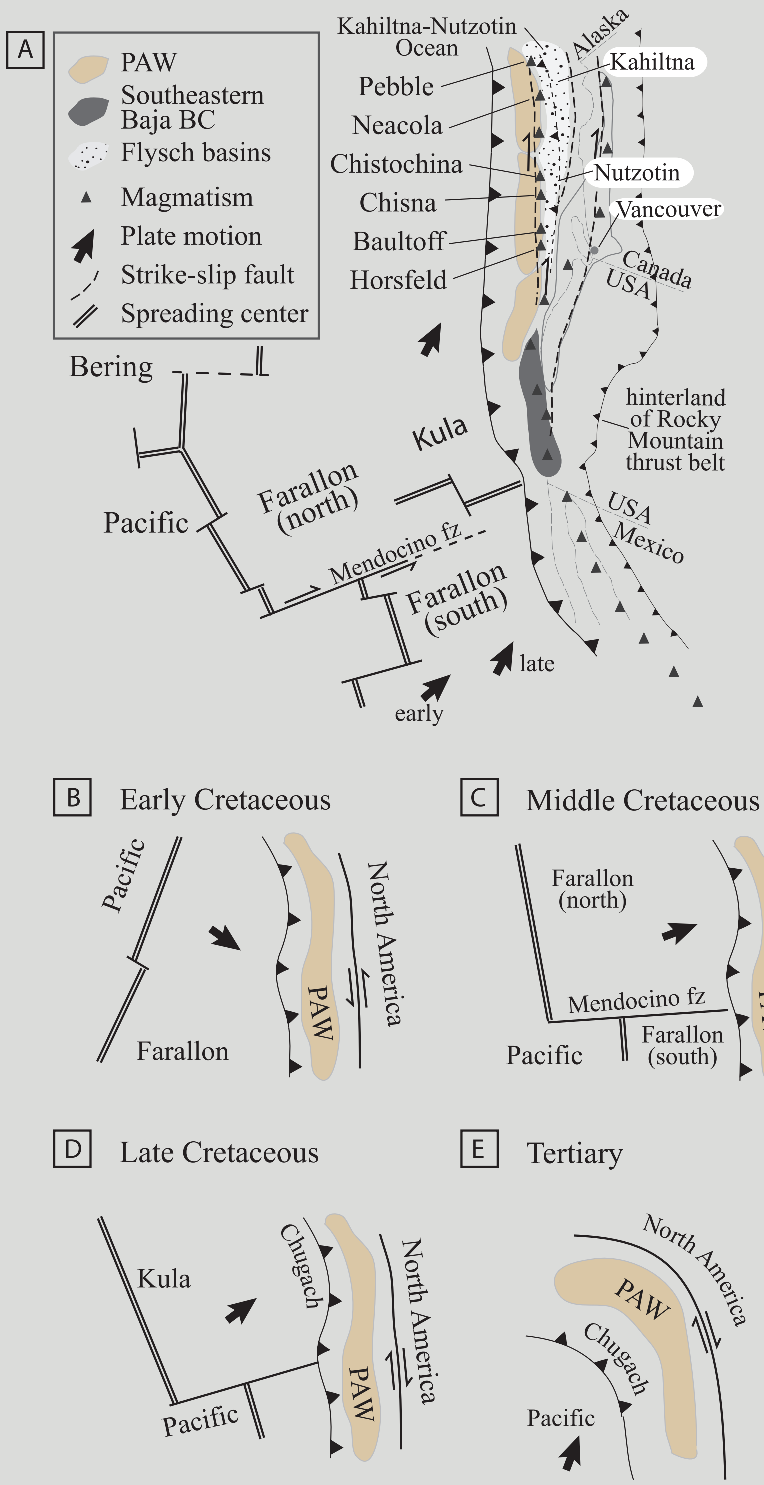


Fig. 31. Palinspastic reconstruction of western North America from the Mesozoic to the Tertiary (generalized from Rea and Dixon, 1983; Umhoefer, 2003; and Smith, 2007). A) One possible scenario for Farallon-Pacific plate spreading during the poorly understood ca. 119-83 Ma period of the Cretaceous Normal Superchron. At some time between 119 and 83 Ma, the Kula plate likely separated from the Farallon plate. Porphyry-related intrusions are dated at ca. 100-90 Ma to the north and at 115-105 Ma to the south along the boundaries of the flysch basins with Wrangellia and Peninsular terranes. The Pebble deposit was the most northerly of the belt of porphyry deposits formed within the diachronously closing Kahiltna-Nutzotin Ocean and then translated along the continental margin. B-E Interpreted time slices of preferred important far-field stresses leading to formation and translation of the middle Cretaceous porphyry deposits. B) Early Cretaceous sinistral translation of Wrangellia composite terrane along the margin of North America. C) Mid-Cretaceous Mendocino fracture zone (fz) splitting Farallon plate into north and south entities. Dextral motion along margin. D) Late Cretaceous Chugach sediments shed into subduction zone. Kula plate now being subducted beneath Wrangellia. Continued dextral translation along margin. E) Tertiary continued buildup of Chugach accretionary complex. Oroclinal bending of Alaska with continued translation of Wrangellia. After Goldfarb et al. (2013).

contains 100–320 Mt grading 0.30–0.35 % Cu and 0.02–0.03 % Mo. The **Bond Creek** deposit (Very Large) contains an estimated 500 Mt grading 0.15–0.40 % Cu and 0.02 % Mo (Young et al., 1997). In addition, Orange Hill is estimated to contain about 45 t Au at 0.15 g/t (Richter et al., 1975). The intrusive complex at Nabesna is associated with typical potassic, phyllic, argillic, and propylitic alteration assemblages, whereas that at Klein Creek only shows potassic and propylitic phases (Hollister et al., 1975; Hollister, 1978). The deposits were included in the Wrangell-St. Elias National Park and Preserve established in 1980 and are thus not exploration targets. However, west of the park, about 100-150 km from Orange Hill, the large Ahtell pluton has been the site of recent exploration for middle Cretaceous Cu-Mo-Au porphyry mineralization (Myers et al., 2010).

The **Nabesna** gold-rich copper skarn is located about 20 km northwest of the Orange Hill porphyry (Fig. 29). A middle Cretaceous pluton of quartz diorite and granodiorite, similar to rocks of the Nabesna batholith, intrudes Late Triassic Chitistone Limestone (Wayland, 1943; Newberry, 1986). The calcic skarn is dominated by chalcopyrite and garnet, with calc-silicate zoning from garnet outward to pyroxene and then unaltered marble (Newberry et al., 1997a). Minor amounts of gold were produced in the first half of the 20th century from pyrite veins cutting the marble and from sulfide-rich skarn.

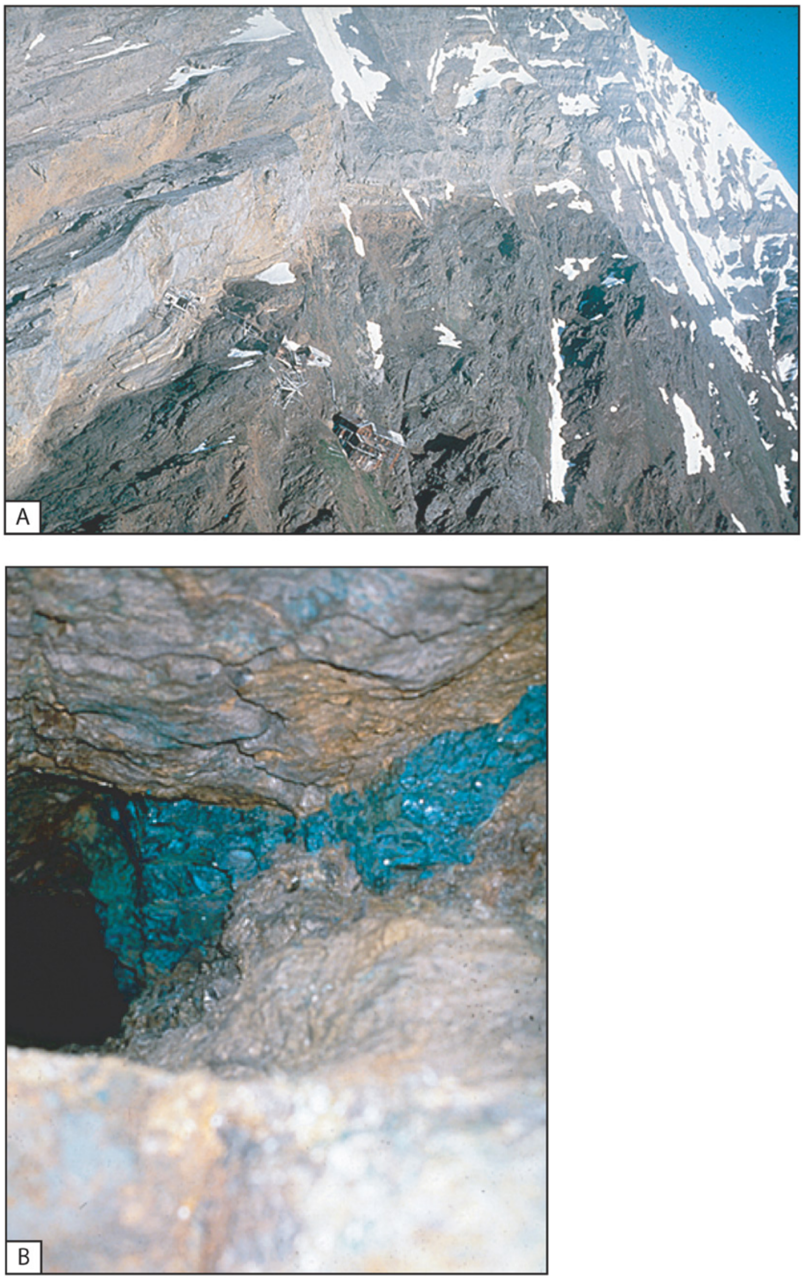


Figure 32. A) The high-grade copper and silver ores were located in steep faults near the base of a Late Triassic limestone (light gray) that overlies the subaerial Nikolai basalt (dark gray), which is believed to be the source of the copper. B) The copper ores are dominantly chalcocite-djurleite that has replaced earlier bornite.

South-central Alaska

Kennecott copper deposits

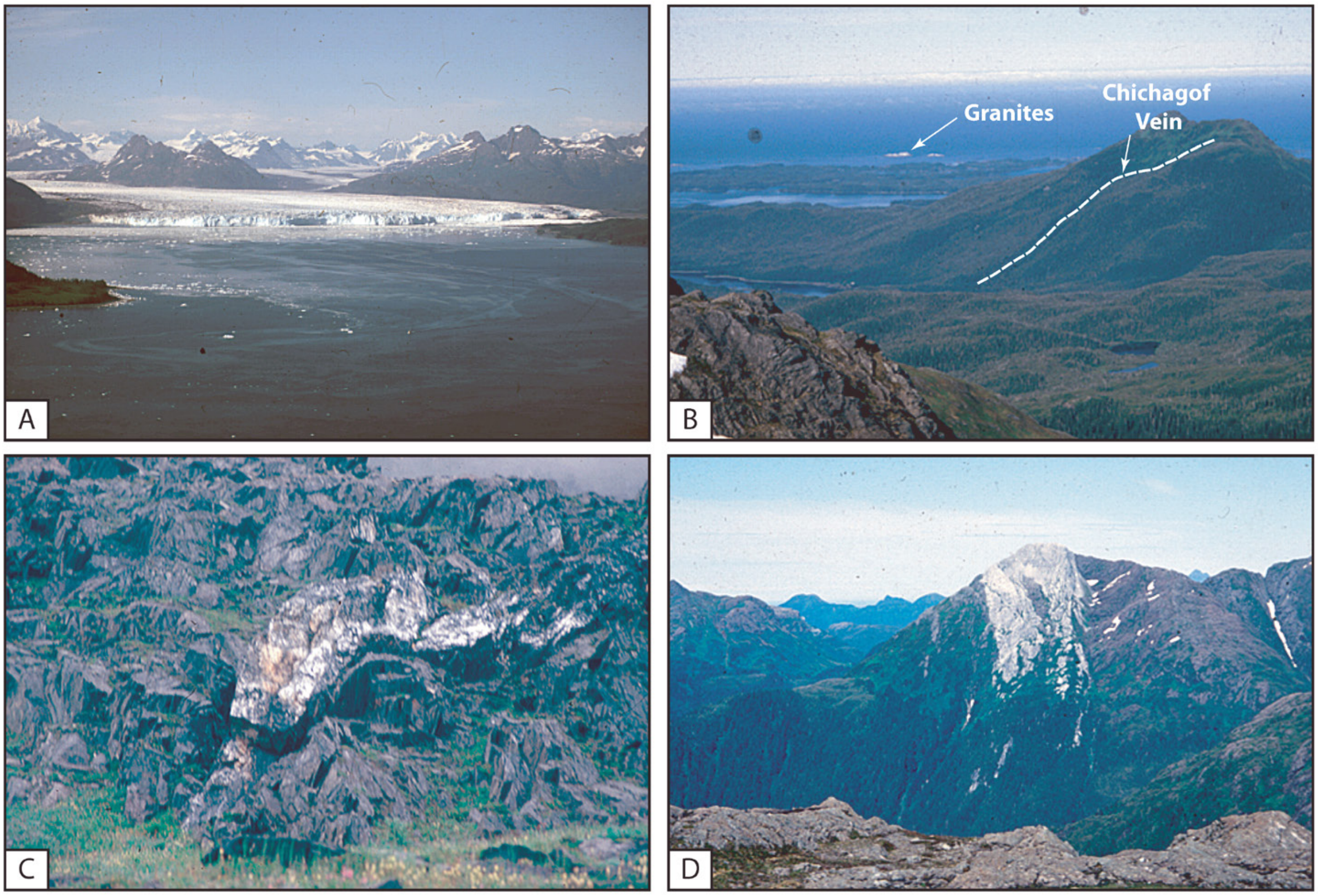
The **Kennecott** copper deposits are located in the southern part of the Wrangell Mountains about 80 km south of the Orange Hill and Bond Creek porphyry deposits and the historic workings are also now within the boundaries of the Wrangell-St. Elias National Park and Preserve (Fig. 29). The copper and silver ores, which were mined from five major deposits (medium sized) (e.g., Bonanza, Jumbo, Mother Lode, Erie, and Glacier), are hosted within steep faults in the base of the Late Triassic Chitistone Limestone of the Wrangellia terrane. They all occur within about 100 m of the underlying subaerial basalt of the Triassic Nikolai Greenstone (Fig. 32A; MacKevett et al., 1997). The high-grade deposits averaged about 13 % copper and were dominated by a chalcocite-djurleite assemblage (Fig. 32B). MacKevett et al. (1997) described a paragenesis where early pyrite was replaced by chalcopyrite, then bornite, and ultimately by the chalcocite and djurleite.

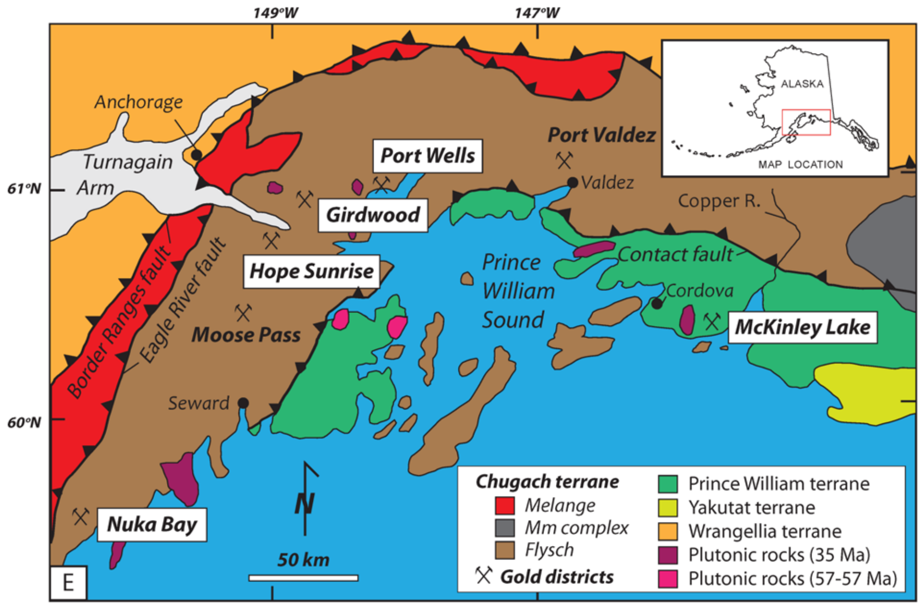
Several different models exist for ore genesis. MacKevett et al. (1997) argued that the ore-hosting faults in the limestone formed during the Jurassic-Cretaceous collision of Wrangellia with North America. Residual brines that were trapped in sedimentary rocks descended into the basalt with a high background concentration of 160 ppm Cu and leached copper. Deposition of sulfides occurred as fluids were focused into the faults in the overlying limestone. As temperatures waned during the hydrothermal event, chalcocite and djurleite replaced the earlier formed bornite. In contrast, Silberman et al. (1978) argued that this final replacement of the bornite was a distinct event that happened in the late Tertiary as young magmatic events facilitated the circulation of meteoric fluids. Silberman et al. (1980) also suggested that a K-Ar age of 112±11 Ma for chloritized greenstone stratigraphically below the main ores represents the age of deposition for the bornite.

Gold metallogeny

Small orogenic gold deposits are scattered through the Chugach and Kenai Mountains and are hosted by flysch of the Valdez Group (Fig. 33A-D). Many occur as discordant quartz veins in saddle reefs (Fig. 33C), joint sets, tensional fractures, and sheared margins to slightly older intrusions within districts such as Port Valdez, Port Wells, Girdwood, Hope-Sunrise, Moose Pass, and Nuka Bay (Fig. 33E; Goldfarb et al., 1986). High-grade veins are typically characterized by abundant wallrock ribbons and, locally, auriferous brecciated veins are important. Arsenopyrite is the most common sulfide phase and coarse visible gold is typical of many deposits. There is little visible wallrock alteration, reflecting both the small size of the deposits and fluids in thermal equilibrium with metasedimentary country rocks (Goldfarb et al., 1986). Most gold deposits in the Chugach and Kenai Mountains are spatially associated with medium greenschist facies Valdez Group rocks, which are characterized by incipient metamorphic biotite. The age of mineralization throughout this part of the accretionary complex is ca. 57-53 Ma (Goldfarb et al., 1997) and the hydrothermal event may be attributed to subduction of a spreading oceanic ridge (Fig. 33F; Haeussler et al., 1995; Bradley et al., 2003).

Orogenic gold deposits of the Willow Creek district are located a few tens of kilometers north of





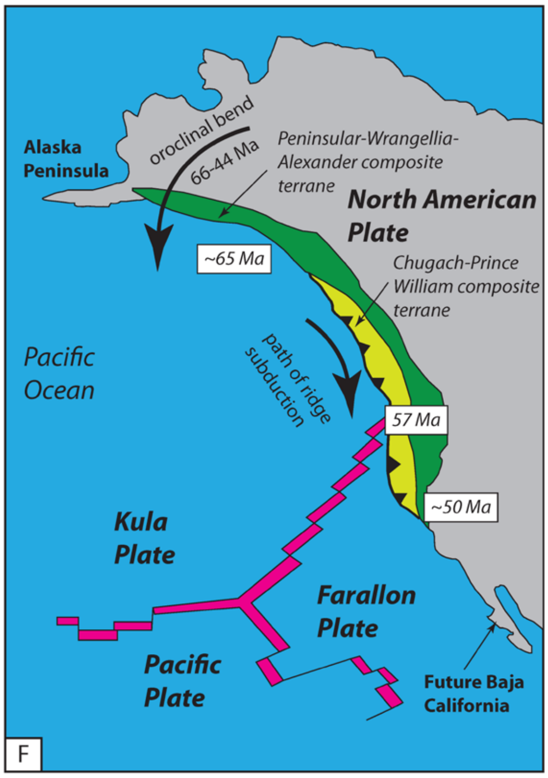


Figure 33. The Chugach accretionary prism (A) extends along the coast of southern Alaska for 2000 km, and makes up much of the Chugach and Kenai Mountains in south-central Alaska and Chichagof and adjacent islands in southeastern Alaska. It was accreted to the seaward side of the Wrangellia terrane, such as shown by the sharp suture contact with the limestone in southeastern Alaska (D). Small gold-bearing orogenic gold deposits are hosted throughout the prism (C), with the largest being those on Chichagof Island (B). Although the deposits are small, they are widespread throughout many districts of the Chugach and Kenai Mountains (E) and are believed to be products of ridge subduction and heating of the base of the accretionary prism between ca. 65 and 50 Ma (F). The spreading ridge migrated to the south, as defined by absolute dates on gold deposits and flysch-melt granitoids, whereas the seaward terranes on the edge of the continent moved hundreds of kilometers to the north during the early part of the Tertiary (After Haeussler et al., 1995)

the Castle Mountain strand of the Border Ranges fault system and within the Early to Middle Jurassic Talkeetna arc developed in the Wrangellia composite terrane. The mines in the district (Fig. 34A; e.g., **Independence, Lucky Shot, Gold Bullion**) defined the largest lode gold producing region north of latitude 60 degrees prior to the development in the past two decades of the Fort Knox and Pogo deposits near Fairbanks. The Willow Creek mines also yielded minor scheelite during World War II. Most of the dozens of gold occurrences are present as auriferous quartz veins in shear zones cutting the southern margin of the Late Cretaceous-early Tertiary Talkeetna Mountains granodiorite batholith that was emplaced into the Jurassic arc (Ray, 1954; Madden-McGuire et al., 1989). Veins show evidence of crack-seal events (Fig. 34B) and more brittle brecciation events, with pyrite as the dominant sulfide, along with gold, tellurides, scheelite, and locally abundant base metal-bearing sulfides and sulfosalts.

The plutonic rocks of the Talkeetna Mountains batholith in the area of the Willow Creek gold deposits were emplaced between ca. 74-67 Ma

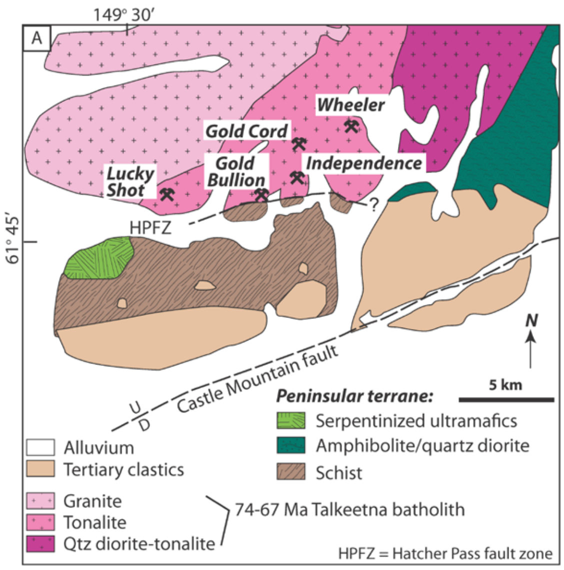


Figure 34. A) Orogenic gold deposits of the Willow Creek district in the Peninsular terrane of south-central Alaska are hosted mainly in the southern margin of the slightly older Talkeetna Mountains batholith. B) Workings at the Independence mine were some of the most extensive in the district, mining high-grade gold from a large crack-seal-type quartz vein.

(Bleick et al., 2012). Most of the gold-bearing veins likely formed at ca. 66 Ma, as the just crystallized batholith was being rapidly uplifted (Steve Harlan, U.S. National Science Foundation, unpub. data). The Castle Mountain fault (Fig. 34A), exposed about 5 km south of the gold deposits and along the edge of the batholith, is estimated to have undergone 130 km of slip post-65 Ma (Pavlis and Roeske, 2007), which would have begun at approximately the time of gold deposition. Such strike-slip motion is commonly associated with regional uplift and formation of orogenic gold ores in a retrograde P-T environment of an evolving orogen (Goldfarb et al., 2005). In the case of the Willow Creek gold district, orogenic gold deposits formed within the margin of the subduction-related batholith itself and not in metamorphosed fore-arc or back-arc regions, as is characteristic of most North American Cordillera settings (e.g., Goldfarb et al., 2008).

Volcanogenic massive sulfides

Paleocene and Eocene metasedimentary rocks and greenstones of the Prince William terrane host massive to semi-massive sulfide occurrences that were developed and mined from 1897-1930 along the fjord margins and on islands of Prince William Sound (A-C). The largest body, producing about 95 % of the copper (83,000 t Cu) from the region, from both open pit and underground workings, was the 300 m x 120 m **Beatson** massive sulfide (Fig. 35A) on LaTouche Island (Bateman, 1924). After the Kennecott deposits, Beatson was the second largest copper producer in Alaska, although mainly economic because of its easy tidewater access and the simultaneous mining of the Kennecott orebodies inland to the north. The numerous VMS occurrences, dominated by pyrrhotite, pyrite, chalcopyrite, and sphalerite (Moffit and Fellows, 1950), are typically localized in sediments deposited along the Kula-Resurrection Ridge that was spreading near the edge of the North American continent (e.g., Bradley et al., 2003). The seafloor volcanism occurred at ca. 57 Ma, shortly before the host rocks for the occurrences were accreted to the continent (Crowe et al., 1992).

Chromite

A belt of dunite and pyroxenite with chromite pods, wisps, bands, and disseminations is discontinuously exposed for more than 1,000 km along the Border Ranges fault system, separating the Chugach and Wrangellia terranes (Guild, 1942; Foley et al., 1997). The largest deposit within the Border Ranges Ultramafic-Mafic Complex at **Red Mountain** (located about 30 km west of Nuka Bay mine on figure 33E) with 1.4 Mt of 5-6 % Cr_2O_3, yielded small amounts of chromium ore during the time of the two World Wars and the Korean War; this mine on the southwestern Kenai Peninsula was the site of the only lode chromite ever mined in Alaska. At Red Mountain, the largest layer of chromite is almost 200-m-long and is as wide as 1.5 m. Platinum group element anomalies are associated with the magmatic chromite in the cumulate ultramafic rocks. The origin of the chromium-rich layers (Fig. 36) remains controversial. Burns (1985) argued that the ultramafic rocks represent the plutonic core

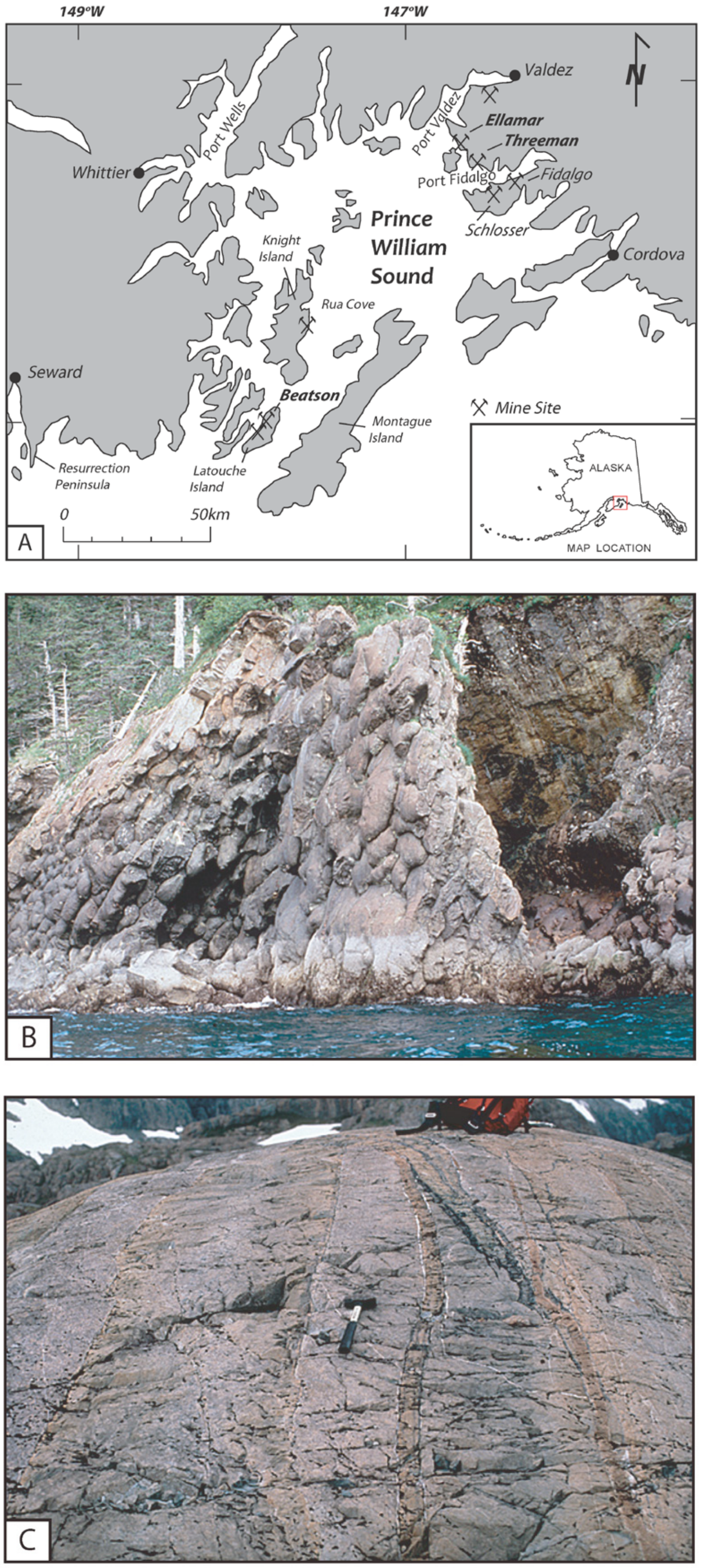


Figure 35. (A) Location of Fe-Cu-Zn VMS deposits in the subduction-accretionary complex rocks, Prince Williams Sound southern Alaska (after Koski et al., 2007). The deposits are in mainly sedimentary rocks, but adjacent to early Tertiary mafic volcanic units associated with a near-shore spreading ridge, including (B) pillow basalts and (C) feeder dikes.

Figure 36. Cumulate ultramafic rocks at Red Mountain, part of the Border Ranges Mafic-Ultramafic Complex of southern Alaska were the site of the only chromite ever mined in Alaska. The chromite layers are present in dunite, such as the 30-cm-wide lens shown here.

of the Jurassic Talkeetna Oceanic Arc, exposed along the terrane suture during Cretaceous accretion and uplift. Alternatively, Kusky et al. (2007) suggested that most of the fault-bounded Late Triassic ultramafic massifs may represent bodies formed in an extensional fore-arc supra-subduction zone seaward of the Talkeetna arc. These were then incorporated within the leading edge of the Chugach terrane during its accretion to Wrangellia.

Southwestern Alaska

Epizonal mercury-antimony deposits

Generally small epizonal mercury and antimony occurrences are scattered throughout rocks of the Kuskokwim basin and, to a lesser extent, surrounding terranes (Sainsbury and MacKevett, 1965; Gray et al., 1997). **Red Devil** (Fig. 37) was the largest of these and the only deposit in Alaska to have produced significant amounts of mercury. The deposits and prospects are mainly present as thin quartz veins in fractures or as breccias in clastic sedimentary rocks, granite sill-dike swarms, and mafic dikes. At Red Devil, however, some of the veins were as much as 1-m-wide and tens of meters in length. Cinnabar and/or stibnite are the dominant sulfides in the veins and breccias, and realgar, orpiment, pyrite, native mercury, and liquid and solid hydrocarbons are also present. Gangue phases include dickite, kaolinite, rare sericite, and carbonate. Anomalous gold is recognized in many of the occurrences (Gray et al., 1990). Dating of hydrothermal sericite indicates metals were deposited ca. 70 Ma,

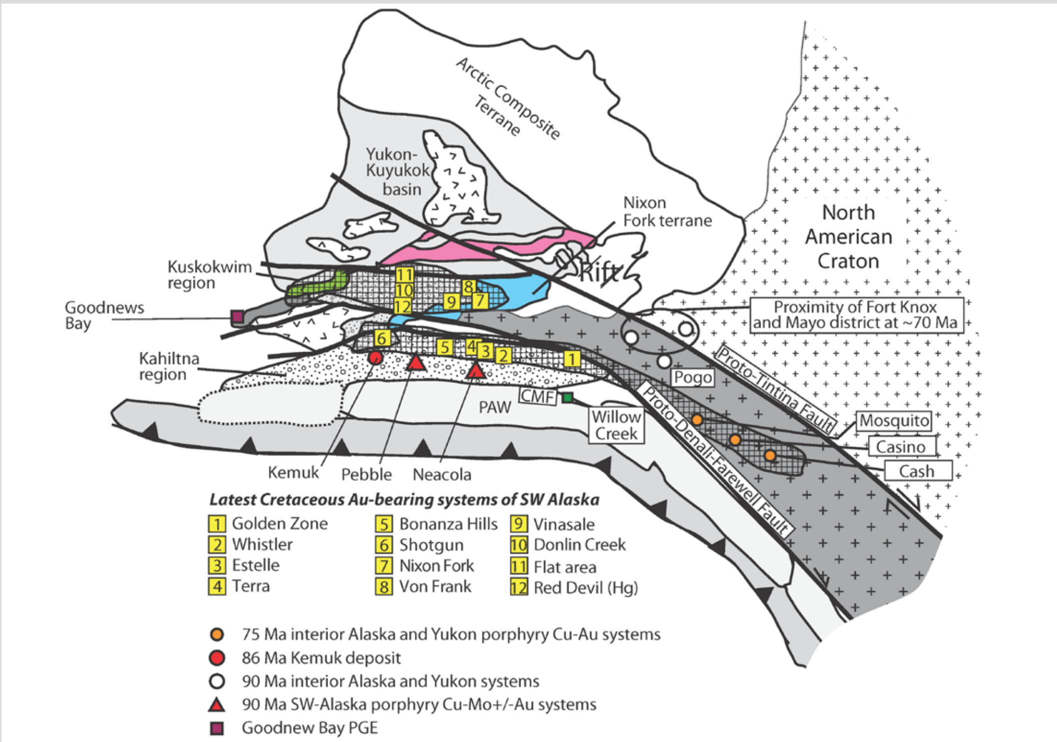


Figure 37. Schematic model of estimated paleo-positions of latest Cretaceous gold-bearing mineral deposits at ~70 Ma in southwestern Alaska from Graham et al. (2013). The model restores dextral displacement along various major faults (Kaltag, Iditarod–Nixon Fork, Denali; Miller and Bundtzen, 2002) and assumes that most movement has occurred since ~70 Ma. Tertiary dextral displacement along the Tintina fault of ~490 km (Saltus, 2007) has been removed. The deposits fall into the Kahiltna and Kuskokwim basin regions (dot pattern and hatched pattern regions). Locations of other deposits to the east shown for reference. Abbreviation: PAW = Wrangellia composite terrane, CMF = Castle Mountain fault.

thus coevally with the late Cretaceous magmatism; there is also a spatial association between many of the occurrences and the granite dikes. Nevertheless, Goldfarb et al. (1990) argued Hg- and Sb-depositing fluids and sulfur were sourced from fluids generated during devolatilization at depth within the Kuskokwim basin.

Gold-bearing deposits

Pluton-hosted gold deposits, the sources for much of the historic placer gold production in southwestern Alaska, are spatially and genetically associated with the latest Cretaceous magmatism throughout the region (Fig. 23, Fig. 37; Bundtzen and Miller, 1997). These deposits have many features that resemble porphyry copper systems, including stockwork style gold and copper mineralization in the cupolas of shallow intrusions. They differ from such deposits, however, by the ilmenite-series chemistry of the host intrusions and lack of well developed porphyry style mineralization, and therefore, at least to some degree, resemble reduced intrusion-related gold systems (Graham et al., 2013). The largest examples of these ca. 70 Ma pluton-hosted deposits are the stockworks and brecciation hosted by syenite, monzonite, and quartz monzonite at **Chicken Mountain**, and the shear-hosted veins in monzodiorite at **Golden Horn** (Fig. 38; Bundtzen et al., 1992; Bundtzen and Millers, 1997). The Cu-Au skarns at the **Nixon Fork** deposit in Ordovician limestones bordering the northern side of the Kuskokwim basin (Fig. 37; Newberry et al., 1997a) and auriferous greisens at the **Shotgun** prospect at the southern end of the basin (Rombach and Newberry, 2001) both may be additional gold deposits closely related to the same magmatism. The approximately 1000 t Cu and 5 t Au recovered from Nixon Fork is the most significant lode gold and copper production from southwestern Alaska.

A number of small gold-bearing deposits (e.g., Yankee-Gaines Creek, Stuyakok), are hosted within the granite porphyry dike and sill systems, similar to many of the mercury and antimony lodes. They consist of finely disseminated Au-bearing arsenopyrite and arsenate minerals and quartz ± carbonate-sulfide veins (Bundtzen and Miller, 1997). In contrast to the pluton-hosted gold deposits described above, these granite porphyry-related deposits lack appreciable

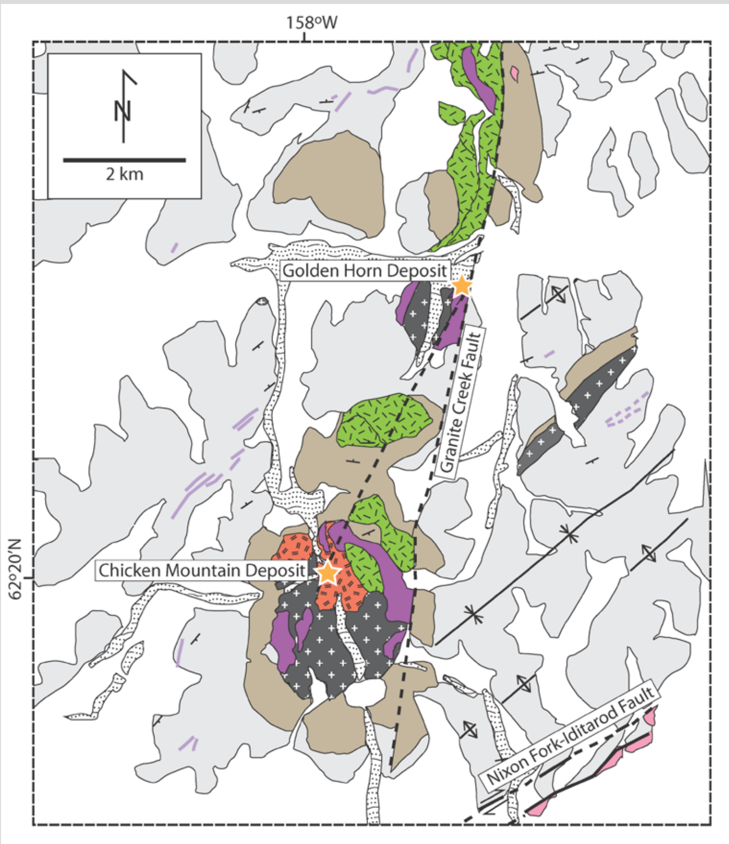
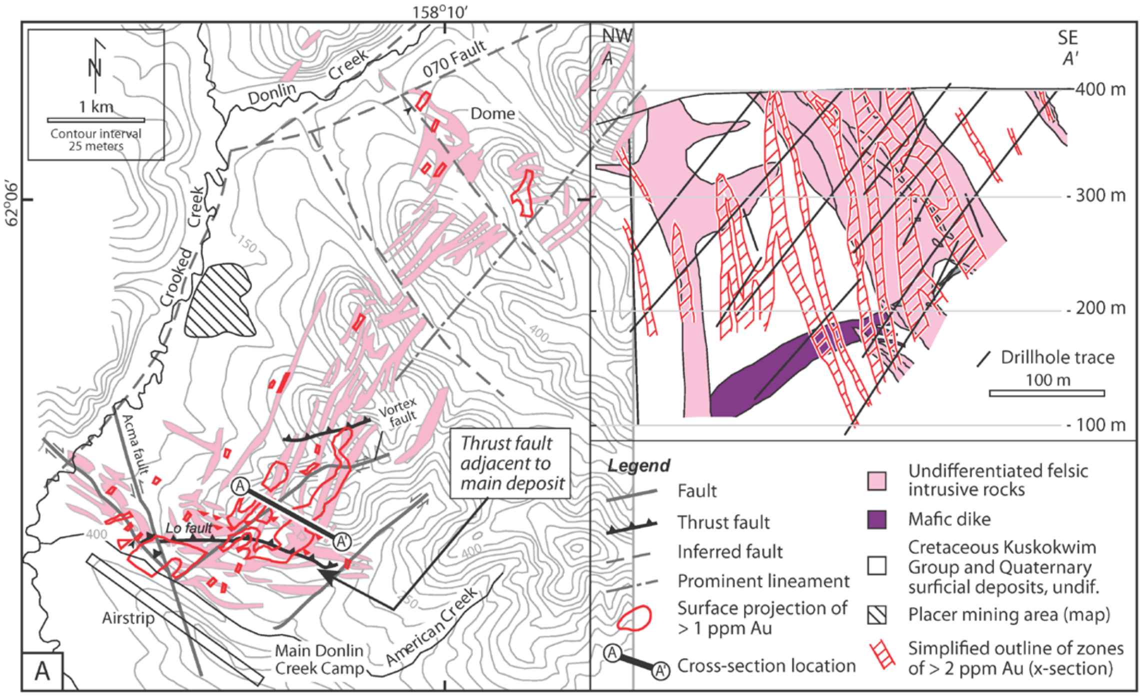


Figure 38. Geological map of Chicken Mountains and Golden Horn deposits near Flat, southwestern Alaska. Modified after Graham et al. (2013).

Cu and are more strongly associated with linear faults or shear zones (Bundtzen and Miller, 1997).

Historically these gold-bearing deposits did not represent economically significant gold resources. However, the **Donlin Creek** deposit (Large) was defined as a giant resource in the late 1990s and is the one significant deposit hosted by the sill and dike complexes (Fig. 39A). It is now estimated to contain a world-class resource (measured+indicated+ inferred) of 1100 t Au at grades of slightly more than 2 g/t (Nova Gold Resources [novagold.com], September 15, 2015). The giant deposit is located along a dilational zone in a subsidiary fault of the Iditarod-Nixon fault system and at the intersection of this NE-striking secondary structure with an east-west-trending regional anticline. The approximately 3 km x 1.5 km group of orebodies are hosted within an 8 km x 3 km, NNE-trending, discordant and porphyritic rhyolitic to rhyodacitic dike-sill complex that intrudes the Cretaceous Kuskokwim Group sedimentary strata. Radiogenic isotope data presented by Goldfarb et al. (2004) suggested that the sill-dike complex was generated by melting of fine-grained sedimentary rocks deeper within the Kuskokwim basin. Nova Gold Resources (Nova Gold Resources website, September 15, 2015) indicates that the mineralized intrusive rocks continue over a vertical extent of a least 945 m.



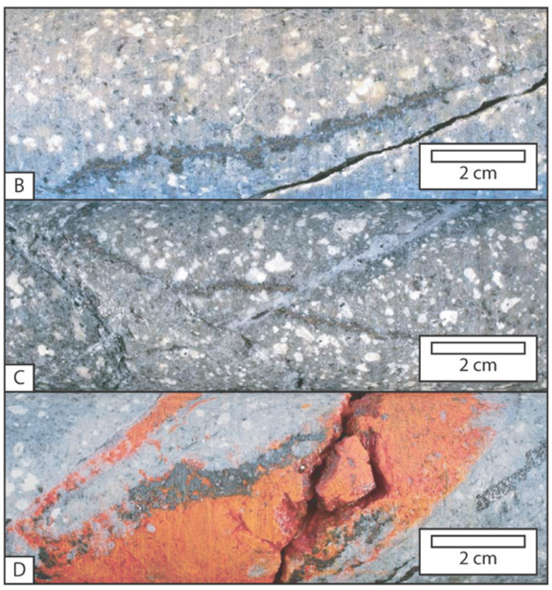


Figure 39. The 1100 t Donlin Creek deposit located in the Kuskokwim basin of southwestern Alaska. A) Plan map showing the NE-trending dike swarm, mapped and inferred faults, and surface projections of ore zones, and a cross section with outlines of mineralized intercepts largely hosted within the brittle granite porphyry dikes. Modified from Graham et al. (2013). B) Early, thin pyrite veinlet cutting rhyodacite porphyry. C) Quartz vein with gold-bearing arsenopyrite selvage cutting earlier pyrite vein. D) Late vein with realgar, native arsenic, and stibnite that overprints earlier auriferous arsenopyrite event. Photos courtesy of Scott Petsel from unpublished report of Piekenbrock and Petsel (2003).

Gold- and sulfide-bearing quartz-carbonate veins and veinlets fill north- to northeast-trending extensional fractures in the igneous rocks (Fig. 39B-D) and in the more competent coarse-grained adjacent sedimentary beds (Ebert et al., 2000; Miller et al., 2000). Most of the brittle veins are only a few centimeters in width and the longest veins are about 7 m. The quartz and carbonate veins generally contain less than 3 % arsenopyrite and stibnite, with traces of cinnabar. Gold is refractory within fine-grained, typically needle-like arsenopyrite in the veins (Ebert et al., 2000). Pyrite is generally present as pre-ore stage veinlets. Late fractures can be dominantly realgar, orpiment, and locally, native arsenic. Fine-grained muscovite and illite are the most widespread alteration phases in the dikes and sills, with also carbonization, sulfidation, and kaolinization. The ages of dike rocks ranged from 74.4 ± 0.8 to 70.3 ± 0.2 Ma ($^{40}Ar/^{39}Ar$; biotite; Szumigala et al., 2000). Mineralization ages between 73.6 ± 0.6 and 67.8 ± 0.3 Ma ($^{40}Ar/^{39}Ar$; Gray et al., 1997; Szumigala et al., 2000) overlap and extend to slightly younger ages than those of the host igneous rocks.

The genesis of the Donlin Creek deposit is controversial. Ebert et al. (2000) identified features characteristic of a low-sulfidation epithermal deposit, whereas a reduced intrusion-related gold system was favored by Lang and Baker (2001). Goldfarb et al. (2004) suggested the very heavy oxygen isotopes, very light sulfur isotopes, and mixed H_2O-CO_2 nature of the ore-forming fluids were more consistent with an epizonal orogenic gold deposit. Although the resource at Donlin Creek makes the deposit a true giant and the largest recognized gold-only type deposit in the North American Cordillera, the refractory nature of the gold ore and the lack of infrastructure in the region surrounding the deposit have hindered development of a proposed open-pit mine.

The western Alaska Range has been the focus of much of the gold exploration in Alaska during the past decade. Gold-rich occurrences that have generated significant interest include the **Whistler** (Large) Au-Cu porphyry (Fig. 40A-B), the **Terra** low-sulfidation epithermal(?), and the **Estelle** ilmenite series pluton-hosted polymetallic vein deposits (Fig. 40C, Graham et al., 2013). The deposits formed between about 76 and 68 Ma in association with the younger

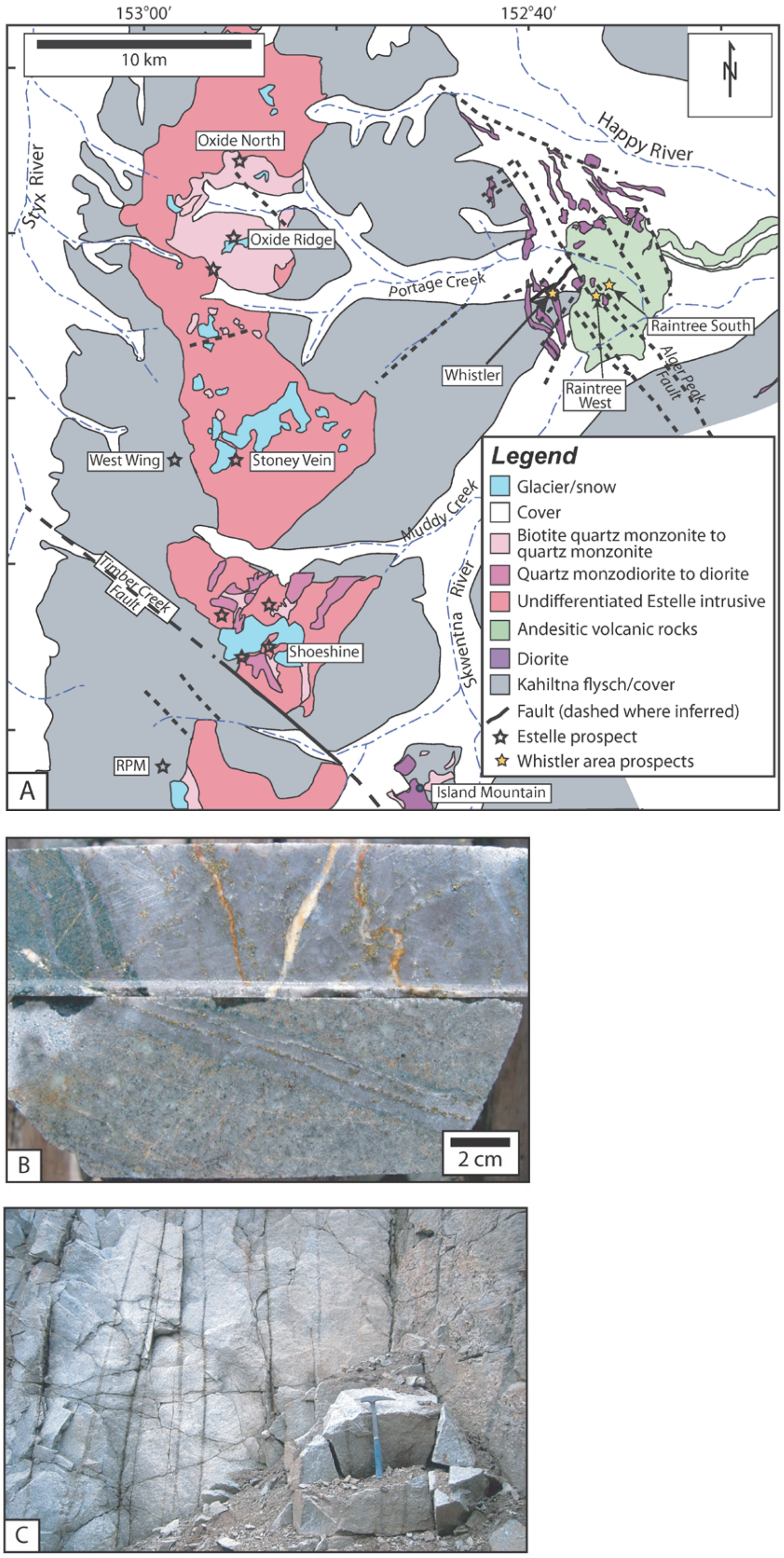


Figure 40. A) Geological map of Whistler and Estelle prospects. Modified after Graham et al. (2013). B) Mineralized Whistler core. C) Estelle prospect mineralized rocks showing outcrop of sheeted vein sets.

period of magmatism within the Kahiltna flysch. The oxidized host diorite at Whistler is associated with the intersection of NE- and NW-striking fault systems, whereas the Estelle pluton and the diorite dike hosting much of the Terra mineralization both are characterized by NNW-oriented vein systems. A paleo-reconstruction of southern Alaska by Graham et al. (2013) at 70 Ma indicates these magmatic-hydrothermal gold systems formed a belt of Late Cretaceous deposits on the more landward side of the Kahiltna flysch basin, relative to the mid-Cretaceous porphyry deposits.

Platinum/palladium deposits

Marine sedimentary rocks and volcanic rocks of the small Goodnews terrane were accreted to southwestern Alaska beginning in Early Jurassic (Box, 1985). As an arc-trench system developed, ultramafic rocks of the early Middle Jurassic Goodnews Bay Complex were emplaced into the terrane and they are now exposed about 150 km south of the mouth of the Kuskokwim River. Placer platinum downstream from the intrusive complex (Fig. 37, Fig. 41), recognized for 90 years, represents the largest PGE resource in the United States (Foley et al., 1997). The complex is a concentrically zoned Urals-Alaska type complex with a dunite-wehrlite core, zoned to a narrow clinopyroxenite zone, outward to a hornblende-clinopyroxenite zone, and then into hornfels country rocks (Foley et al., 1997). The dunite is highly serpentinized, with 10-60 % of exposed rock showing olivine altered to serpentine. Platinum is associated with chromite and magnetite in the dunite core, whereas palladium is associated with pyrrhotite and chalcopyrite in the pyroxenite (Mertie, 1976; Southworth and Foley, 1986). Despite the huge placer endowment, no economic PGE lode sources have been recognized; this may reflect erosion of the most significant PGE occurrences or the highly disseminated nature of the PGEs (Mertie, 1976).

In the Nushugak lowlands, in southernmost southwestern Alaska (just south of 60°), an aeromagnetic anomaly identified in 1959, in a region with 300-m-thick Quaternary cover, was subsequently drilled to identify a large mafic-ultramafic intrusion emplaced into sedimentary rocks of uncertain affinity. The composite clinopyroxenite and gabbro bodies contain zones of high-grade titaniferous magnetite, Cu-Zn sulfides, and anomalous platinum (Foley et al., 1997). This **Kemuk** prospect, dated at ca. 86 Ma (Iriondo et al., 2003), was classified by Foley et al., (1997) as a Urals-Alaska type complex of zoned mafic-ultramafic rocks.

Alaska to the south of 60 degrees

The southernmost parts of Alaska, to the south of 60 degrees, contain additional significant metallic mineral resources. The southeastern Alaska panhandle region, due to its complex geology of numerous narrow, lengthy, fault-bounded terranes, is probably the most metal-rich part of Alaska. It includes many pre-, syn-, and post-ac-

Figure 41. Platinum mine dredge downstream from ultramafic rocks, Salmon River, Goodnews Bay region, southwestern Alaska. Photo courtesy of Gary T. Mason.

cretionary ore deposits formed at different crustal depths over more than 500 m.y.. The southern part of southwestern Alaska hosts the giant Pebble porphyry Cu-Au-Mo deposit, which contains the world's largest known igneous rock-hosted gold resource. Other porphyry and epithermal prospects exists further south along the Alaska Peninsula-Aleutian Island chain.

Southeastern panhandle

The two largest gold producing areas of the 20th century in Alaska were the Juneau gold belt and the Chichagof district. The orogenic gold deposits in the Juneau area occur along a 160-km-long by 5- to 8-km-wide structurally deformed zone centered around the suture between a Jurassic-Cretaceous flysch basin sequence and older parautochthonous terranes, about 15-20 km seaward of the generally slightly older, subduction-related Coast batholith (Fig. 42A-B) Goldfarb et al., 1988). The largest deposits, including those at the historic **Alaska-Juneau** (Fig. 42C) and **Treadwell** mines, which yielded slightly less than 200 t Au combined prior to World War II, and at the presently active **Kensington** mine, are hosted by pre-ore competent intrusive bodies that were emplaced within the metasedimentary rock sequences. The deposits mainly formed along giant shear and tensional vein systems at ca. 56-53 Ma during seismic events associated with changes in Pacific basin plate motions (Goldfarb et al., 1991; Miller et al., 1994). Seaward of the Juneau gold belt, the **Chichagof** (Fig. 33B) and **Hirst-Chichagof** orogenic gold deposits were mined in the first half of the 20th century from local shear zones cutting metasedi-

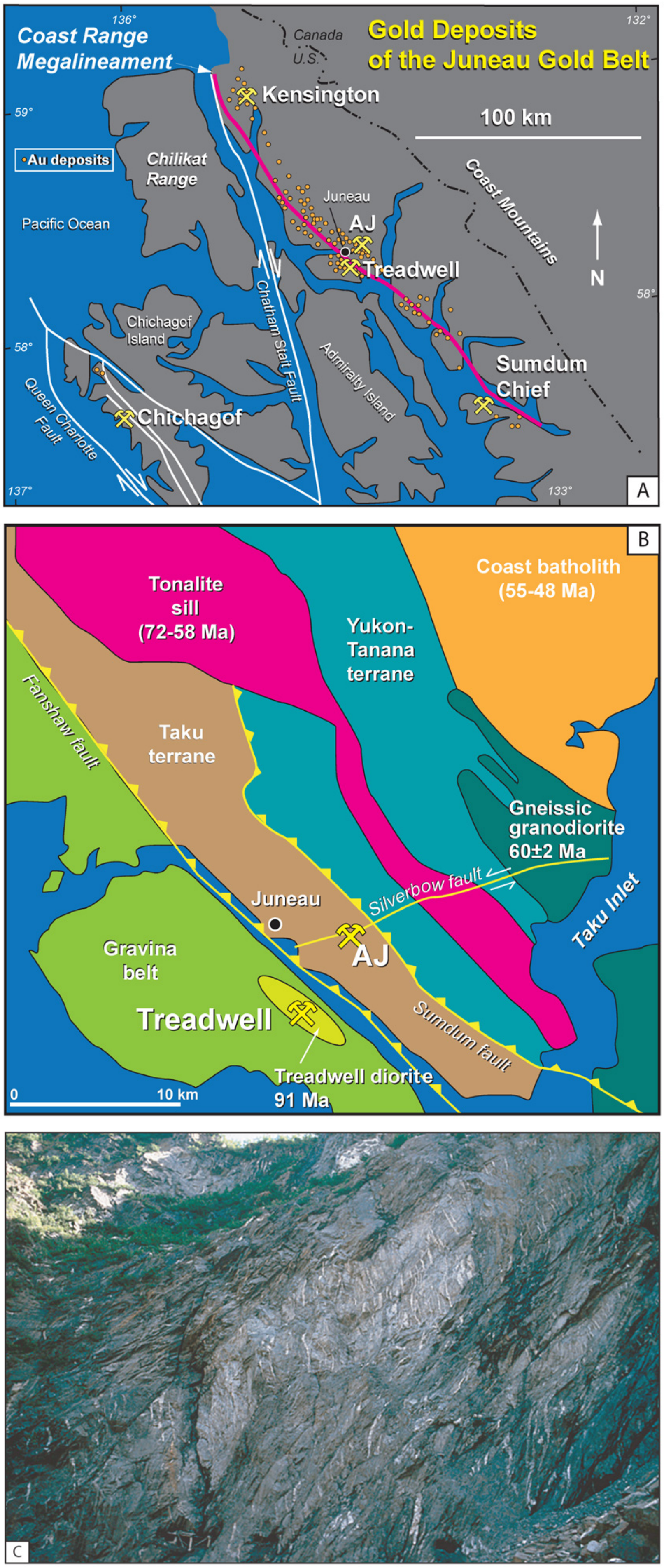


Figure 42. The Juneau Gold Belt of southeastern Alaska was the largest historic gold producer in Alaska. A) The 160-km-long Juneau gold belt, SE Alaska, includes numerous deposits along the length of a complex structural zone, sometimes termed the Coast Range Megalineament (CRM), This zone includes two closely-spaced thrust faults that represent mid-Cretaceous sutures of terranes being added to the Cordilleran orogen. B) Geology of the central part of the Juneau gold belt in the area of the ca. 55 Ma Alaska-Juneau (AJ) and Treadwell deposits. A syndeformational belt of tonalite sills was emplaced 5-10 km landward of the gold deposits between 72 and 58 Ma. Subsequently, post-kinematic plutons of the Coast batholith were emplaced east of the sills. C) Gold ore in AJ pit preferentially hosted in veins in competent diorite bodies. Figure 41. Platinum mine dredge downstream from ultramafic rocks, Salmon River, Goodnews Bay region, southwestern Alaska. Photo courtesy of Gary T. Mason.

mentary rocks of the Chugach accretionary complex. These ca. 50 Ma crack-seal vein systems have been suggested to be products of the same ridge subduction event (Fig. 33F) that led to formation of smaller gold deposits described above in the Chugach-Kenai Mountains (e.g., Haeussler et al., 1995).

Allochthonous rocks of the Wrangellia composite terrane in southeastern Alaska host a number of belts of different aged sea-floor VMS deposits that formed far from the present-day Alaskan continental margin. Small metamorphosed and deformed latest Proterozoic to Cambrian and Ordovician to Early Silurian deposits are located in southernmost southeastern Alaska and were mined mainly for their copper, zinc, and precious metals in the early 1900s (Fig. 43; Newberry et al., 1997b). The older occurrences, such as **Niblack** and **Khayyam**, represent the oldest recognized mineral deposits in Alaska. A more significant belt of VMS deposits, associated with Late Triassic rift-related bimodal volcanism, stretches for 400 km along much of the panhandle (Fig. 43), and to the north into British Columbia, Canada, where the giant Windy Craggy Cu-Co-Au deposit (190 Mt of 1.6 % Cu and 0.2 g/t Au) is located (Peter and Scott, 1999), although in a park area closed to mine development. The VMS deposits include **Castle Island**, which was the site from 1963 to 1980 of the only barite mined in Alaska, and of the presently active **Greens Creek** mine. The latter Zn-Pb-Ag-Au deposit, the United States' largest silver producer, formed exhalative to replacement style ores in a shallow propagating intra-arc setting along the contact between argillite and mafic flows (Taylor and Johnson, 2010).

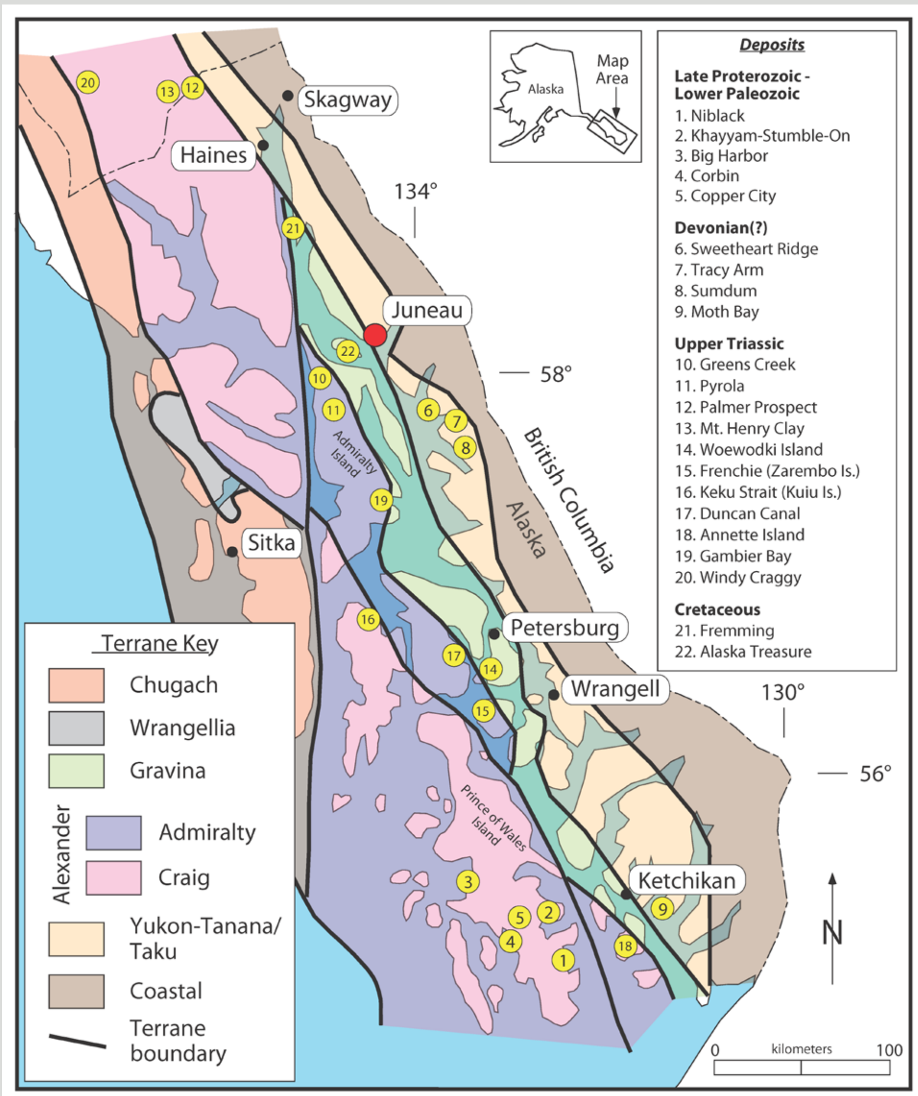


Figure 43. Generalized map of terrane boundaries (bold lines) and major VMS deposits, southeastern Alaska. The Late Triassic deposits, including Greens Creek, occur along the length of the SE Alaska panhandle within the Alexander terrane of the Wrangellia composite terrane and are the most significant of the deposits. Modified from Taylor and Johnson (2010).

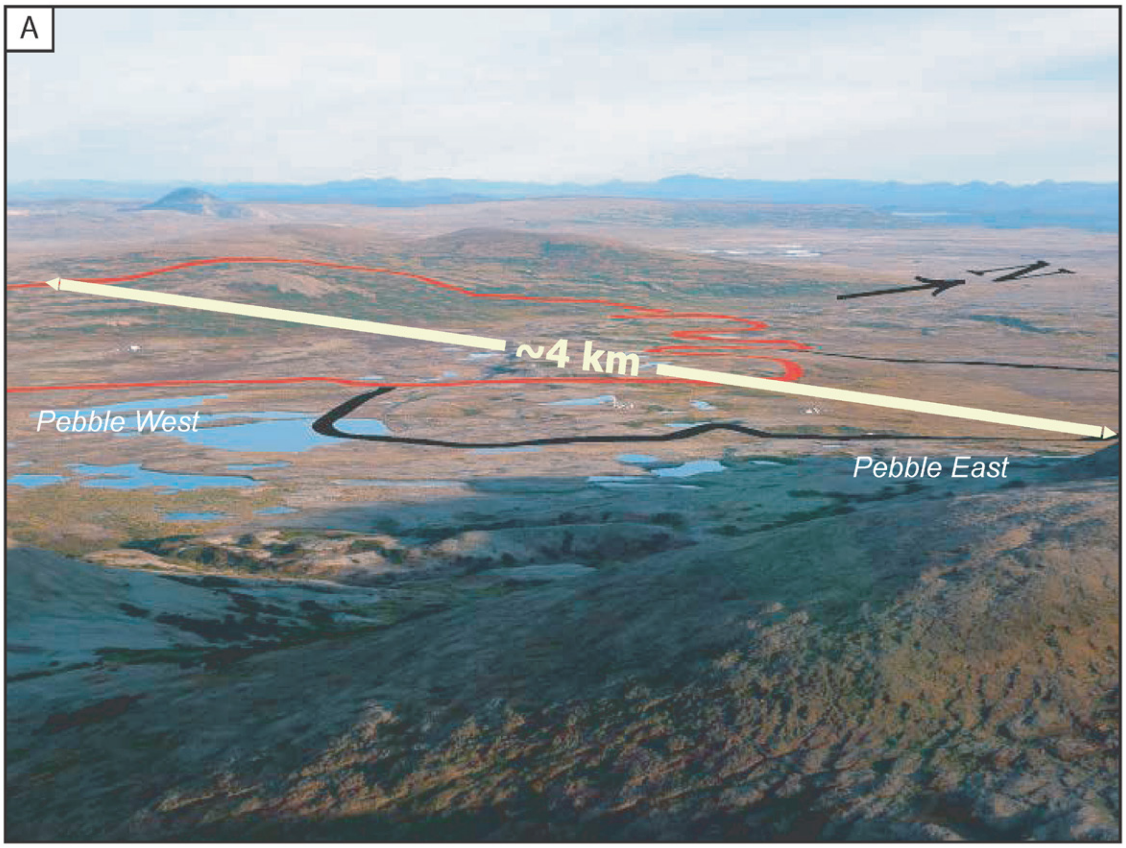
The southeastern Alaskan panhandle also hosts a number of other important magmatic and magmatic-hydrothermal ores. The **Quartz Hill** porphyry molybdenum deposit mentioned earlier is hosted by a rift-generated Oligocene felsic stock emplaced into a calc-alkaline subduction-related arc (Ashleman et al., 1997). The deposit, the largest arc-related type porphyry molybdenum deposit in North America, also possesses some features that are more characteristic of the extensional alkali-feldspar rhyolite-granite porphyry molybdenum deposit group and may be more of a hybrid deposit between the two deposit types (e.g., Taylor et al., 2012). This part of Alaska is also one of the type localities for ores that are typically referred to as Urals-Alaska type zoned mafic-ultramafic complexes. The undeveloped, 40-km-wide, roughly syn-accretionary, mid-Cretaceous Klukwan-Duke belt of these intrusions stretches for >500 km along the length of southeastern Alaska (Fig. 5), with 15-20 % Fe in the outer hornblende-pyroxenite part of the complexes and Pt-bearing chromite in the dunite cores (Foley et al., 1997). A group of poorly studied ca. 40-30 Ma composite tonalite, gabbro, and norite bodies, which intrude the Chugach accretionary prism in the northern part of the panhandle, host Cu-Ni-PGE mineralization in the more mafic intrusions. These include the **Brady Glacier** deposit, closed to mining in a remote part of Glacier Bay National Park, which represents one of the United States' largest nickel resources (Foley et al., 1997).

Southern Southwestern Alaska and Alaska Peninsula-Aleutian Island Chain

The giant **Pebble** Cu-Au-Mo deposit, located 320 km southwest of Anchorage and containing the largest gold endowment of any porphyry deposit in the world (3033 t Au grading 0.35 g/t), is associated with ca. 90 Ma intrusive bodies of the Kaskanak batholith emplaced into the Jurassic-Cretaceous Kahiltna flysch (Fig. 44, Lang et al., 2013). It may have been the northernmost of a series of porphyry deposits formed along the landward margin of the Wrangellia composite terrane in the mid-Cretaceous many hundreds of kilometers south of their present latitude (Fig. 8, 31); other deposits of the belt, described above and shown on figure 5, are exposed in the high elevations of the eastern Alaska Range (Goldfarb et al., 2013). The Pebble deposit formed during 10 million years of magmatism, beginning with emplacement of granodiorite and diorite sills, early alkalic intrusions and related breccias, and finally intrusion of the 90 Ma subalkalic granodiorite Kaskanak batholith, with those rocks along the batholith margin hosting the mineralization (Lang et al., 2013). Lang et al. (2013) suggest the large size of the deposit, as well as its high-grade hypogene ore, reflect multiple episodes of magmatic-hydrothermal events, an effective synhydrothermal fault zone for fluid focusing, and overlying hornfels zones in the flysch forming an aquitard to the upward fluid movement.

The Pebble deposit is divided into the Pebble East Zone and Pebble West Zone, which define two associated hydrothermal centers with the east zone dropped 600-900 m in a graben (Kelley et al., 2013). Pebble West extends from the near surface to 500 m depth, whereas Pebble East, below 300-600 m of Late Cretaceous to Eocene sedimentary and volcanic rock cover, continues to depths below 1700 m (Lang et al., 2013). There is a small zone of supergene mineralization above the West Zone orebody, but generally all ore is hypogene. The chalcopyrite±bornite, pyrite, free gold, and electrum are associated with potassic and sodic potassic alteration, with a kaolinite and illite alteration event redistributing the metals. Areas of extremely high-grade Cu and Au mineralization are associated with a zone of relatively late advanced argillic alteration that was focused in the Pebble East Zone. Rhenium-rich molybdenite was introduced during a late quartz vein episode (Lang et al., 2013). Interpretation of reduced-to-pole aeromagnetic data suggests that similar porphyry-style mineralization may exist below cover elsewhere in the northern part of the Alaska Peninsula (Anderson et al., 2013).

To the southwest, the continental arc transitions into the Cenozoic Aleutian oceanic arc. Porphyry and epithermal prospects are widespread along the arcs (e.g., Wilson and Cox, 1983), but the remoteness, lack of infrastructure, and presence of protected wildlife refuges of the region have hindered exploration programs. Low sulfidation epithermal Au-Ag deposits of the Shumagin Islands, such as the **Alaska-Apollo** deposit, have seen some minor development and production (Wilson et al., 1996).



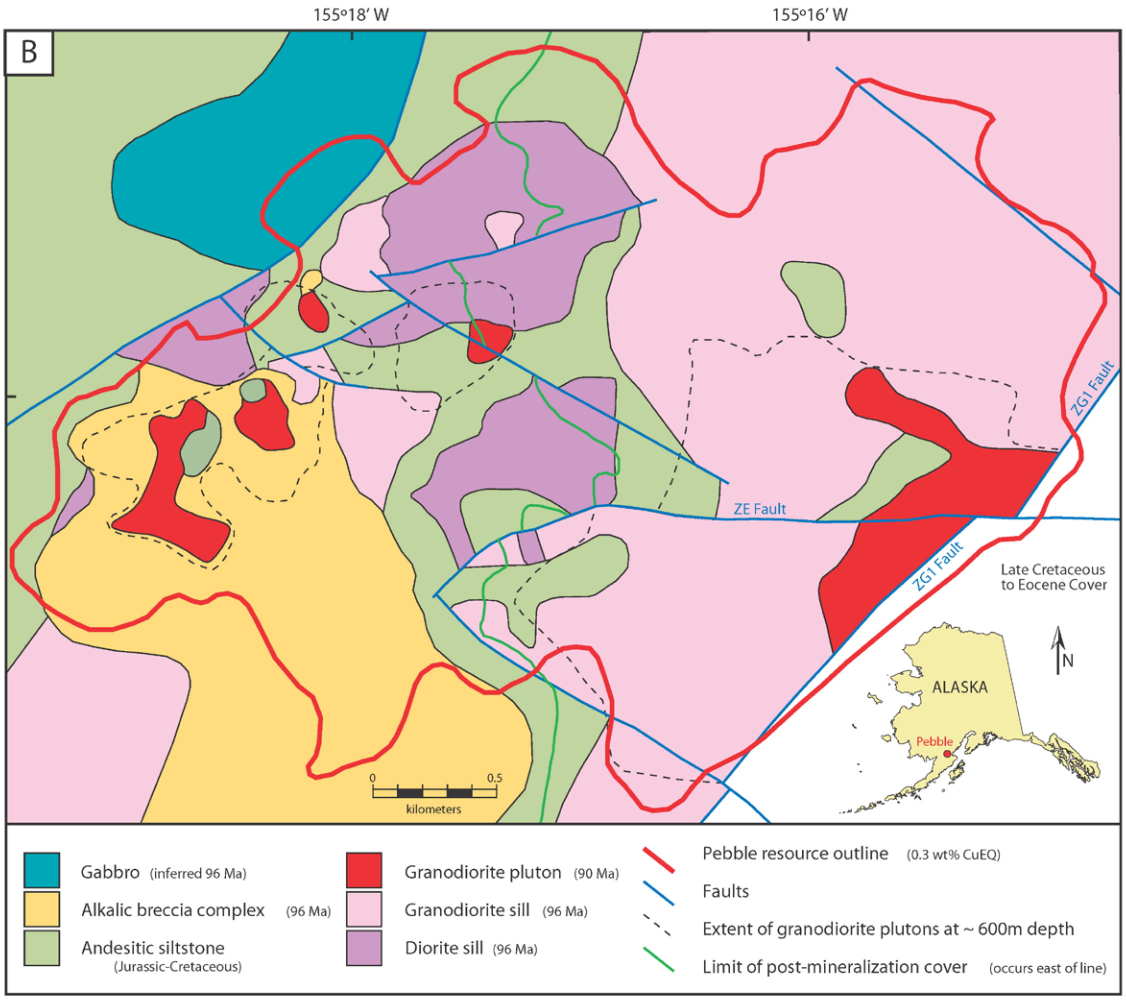


Figure 44. A) The location of the giant Pebble Cu-Au-Mo porphyry deposit, in largely concealed terrain, showing the surface expression of the Pebble West Zone (red outline) and Pebble East Zone (black outline) in southern southwestern Alaska (from Gregory et at., 2013). B) Geologic map of the ca. 90 Ma Pebble porphyry deposit. Courtesy of Karen Kelley, USGS.

ALASKA'S FUTURE

Alaska's relatively short history of mineral exploitation, barely more than 100 years, and the reconnaissance nature of geologic knowledge for much of the State allow the possibility of major undiscovered ore deposits. The known very large ore deposits have been discovered relatively recently (since ~1970) and in the case of the Fort Knox gold deposit, represent a new, previously unexpected mineral deposit type. It is likely that other major metallic mineral resources remain to be discovered in this region of extremely complex and prospective geology. The known large deposits north of 60 degrees are base and precious metal deposits, as are the vast majority of known mines and prospects. For much of modern history, gold has been an important driver of mineral exploration in Alaska, yet a number of the very large deposits, for example Red Dog and Bornite, are base metal deposits containing little or no gold.

The major known metallogenic provinces, for example those hosting the polymetallic base metal deposits of the Brooks Range and eastern Alaska, and the more widespread gold and porphyry deposits spread across different parts of Alaska, reflect ores formed in quite different temporal and tectonic environments. The VMS and clastic-dominated Pb-Zn provinces reflect largely stratabound Paleozoic mineralization formed in ocean basins that is overprinted in many cases by mid-Cretaceous metamorphism. The gold provinces throughout much of Alaska and porphyry belts in the southern part of the State primarily reflect mid-Cretaceous to Eocene tectonism along active continental margins. Both metamorphism and magmatism may have been significant in the formation of various lode gold deposits; erosion of lodes has led to many large and productive placer gold fields.

Major brownfield and greenfield discoveries are both likely to be part of Alaska's exploration future. Brownfield developments will be highly influenced by socioeconomic issues. The Fort Knox deposit, for example, was explored and developed at the site of a gold occurrence known for almost 100 years, but a favorable infrastructure near the town of Fairbanks and a local population that mainly supported the nearby mining activity were critical for success. Giant mineral deposits are now recognized at Donlin Creek, Money Knob, and Pebble, but issues of infrastructure, metal price, and/or potential environmental effects are impacting their additional exploration and potential development. The successful model of sustainable resource development in the Red Dog district, with beneficial inclusion of the Native Alaskans in all stages of activity, provides an example that could be followed for future mining of other large tonnage deposits in many parts of the State. Pebble and Pogo represent recent greenfield exploration successes that indicate numerous giant deposits still remain to be discovered throughout Alaska, particularly in the relatively poorly understood areas of extensive young cover. State-of-the-art approaches in exploration geochemistry, remote sensing, and particularly geophysical methods will be required for better defining geology and structure in many of these areas of cover and identifying the most favorable areas for discovery of important resources.

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