Mineral Deposits of Alaska

RICHARD J. GOLDFARB AND LANCE D. MILLER, EDITORS

False color, composite satellite image of Alaska and adjacent Yukon Territory.

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The simulated color-infrared (CIR) image is a composite of NOAA/Advanced Very High Resolution Radiometer scenes collected during the summer of 1991. Daily scenes were analyzed to select the day for each picture element with the maximum Normalized Difference Vegetation Index (NDVI), a measure of photosynthetic activity. This method of composing minimizes the clouds, an important consideration in some parts of Alaska, and depicts the vegetation at the height of its growth. The image is built by displaying the sensor's infrared band in red, the visible-red band in green, and an estimated green band, displayed in blue. The resultant simulated CIR image shows the deciduous vegetation in brighter reds, coniferous forest in darker reds, and areas of tundra and lake mosaic, or alpine tundra, in blues and greens. Image generated by Michael D. Fleming, Images Unlimited, Anchorage, Alaska.
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Mineral Deposits of Alaska

Preface

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Mineral resources have been important to the Alaskan economy for hundreds of years. The Indians, Eskimos, and Aleuts used gold, copper, and other metals for jewelry, utensils, and weapons and as items of trade. The Russians, who arrived in 1728, showed only minor interest in minerals, focusing instead on furs. Nonetheless, records show that they mined iron ore on the Kenai Peninsula in 1733 and located gold there in 1834. In addition, the Russians were aware of copper-rich occurrences in the Copper River basin.

The mining industry grew rapidly in Alaska after the United States purchased the region from Russia in 1867. By 1870, gold was being mined near Windham Bay and near Sitka, in southeastern Alaska. The first major hard-rock gold mining began at the Alaska-Juneau, Perseverance, and Treadwell mines near present-day Juneau following the discovery of placer gold near tidewater in 1880. Significant placer mining operations for gold soon spread northward into districts such as Fairbanks, Nome, Iditarod, and Circle.

The exploitation of mineral resources, particularly gold, influenced the settlement and development of much of the state. Major cities such as Nome, Fairbanks, and Juneau, the capital, were originally built around early mining camps. By 1906, more than 33 million oz of gold, as well as significant amounts of copper, lead, zinc, silver, and platinum-group elements, had been produced. In addition, there has been minor production of nickel, tin, mercury, and uranium.

Alaska is presently experiencing a renaissance in mining on federal, state, private, and native lands. From 1990 to 1996, the minerals industry had an annual value of approximately $600 million, with a record 1 billion in 1996. Nearly 3,500 year-round jobs were directly attributed to the minerals industry. Looking forward into the twenty-first century, the outlook is even better. Major mines such as Red Dog are in production. Recently completed exploration at the Red Dog sedimentary exhalative deposit has significantly expanded the reserve base and major mine expansion is contemplated. The Nixon Fork gold skarn deposit was put into production in 1995, with the first ore poured in November. The Greens Creek mine resumed production in late 1996, following renewed exploration and development of the volcanogenic massive sulfide deposit. The Fort Knox gold mine, near Fairbanks, is under construction and is scheduled to yield ore by late 1996. In southwest Alaska exploration success has yielded a significant gold resource at Donlin Creek. In addition, the Kensington-Juwin project is at an advanced stage. Recent actions by the state of Alaska with regard to government-sponsored geophysical mapping, land-use priorities, environmental regulations, taxation, and mineral exploration incentives suggest that responsible growth of the minerals industry will be favored there as projected oil-based revenues decline sharply throughout the remainder of the decade.

Alaska clearly remains elephant country, as evidenced by the discovery of four world-class ore deposits (Greens Creek, Red Dog, Fort Knox, and Quartz Hill) in the past twenty years. Because of the great mineral potential of the state, we believe this monograph will serve as a useful guide to the economic geology of the many and varied mineral deposit types within Alaska. Much of the description will remain useful well into the future. Some of the interpretations may indeed change as more information becomes available about specific deposit types; however, the genetic models presented here reflect our geologic understanding of these mineral systems in the 1990s. In addition to being a useful reference for mineral deposits in the state, the metallogenic setting of Alaska's deposit is similar to other parts of the Pacific Rim, where much exploration and mining is presently being focused. Therefore, this monograph should also be a useful reference for geologists working in cordilleran-type settings that extend beyond the borders of Alaska.

This monograph contains 15 papers. The first is an overview describing the metallogenic evolution of Alaska. Goldfarb (1997) takes us forward in time and synthesizes the tectonic development of Alaska and associated ore formation in oceanic environments between 700 and 150 Ma. Deposits associated with oceanic settings include shale-hosted Zn-Pb-Ag carbonate-hosted copper, and polymetallic volcanogenic massive sulfide deposits. The last 150 m.y. are characterized by collisional tectonics, voluminous calc-alkaline magmatism, and the formation of epigenetic Cu and Mo porphyry deposits, skarn deposits, epithermal precious metal systems, Fe-rich Alaska-type zoned ultramafic bodies, and mesothermal gold lodes.

Among the world-class ore deposits in production in Alaska, the Red Dog mine stands out. In the paper on shale-hosted Zn-Pb-Ag and barite deposits of Alaska, Schmidt (1997a) describes Red Dog as a vent-dominated end member of the shale-hosted type of massive sulfide deposits. Most of the significant shale-hosted mineralization in northern Alaska is shown to be within Carboniferous rocks that are mainly associated with restricted basins proximal to extensional faults. In a related chapter, Schmidt (1997b) describes two types of strata-bound carbonate rock-hosted deposits in nearby platform environments that represent additional base metal-rich exploration targets developed along the passive
North American Paleozoic continental margin. The first type, which she favors as being similar to Mississippi Valley-type or Irish-type deposits, includes Zn-Pb ± Ag stockworks, lenses, breccias, and disseminations; the second deposit type includes epigenetic stockworks of Cu-Co ± Zn. Schmidt synthesizes and presents the available information on both the shale- and carbonate-hosted deposit types, concluding each chapter with a discussion of the potential for favorable host rocks in Alaska.

It takes a rare deposit to make a major mining company, such as the replacement copper ores in the Wrangell Mountains did for Kennecott. In the paper on the Kennecott deposits, MacKevett, Cox, Potter, and Silberman (1997) describe and evaluate the unique setting of these deposits and propose a model of ore genesis in which oxidized copper-bearing brines circulated through the Nicolai greenstone. The copper was deposited at low temperatures in karst-type openings that exploited a series of northeast-striking joints. Although this type of deposit is not widely recognized, its characteristics serve as a reminder that not all deposit styles fit established models. Hence, the explorationist should beware.

Ninety percent of the gold production in Alaska has been derived from Cretaceous and early Tertiary lode deposits and associated placers in metamorphosed terranes. In the paper on gold deposits in metamorphic rocks of Alaska, Goldfarb, Miller, Leach, and Snee (1997) present the regional setting as well as the geochemical, structural, and mineralogical characteristics of the major lode systems in the state. These deposits all formed under mesothermal pressure-temperature conditions in greenschist facies rocks. Mass balance work supports the hypothesis that gold was mobilized from background concentrations in midcrustal rocks and that the ore-transporting fluids have a metamorphic signature. Goldfarb and the others summarize their paper with a genetic model in which the lode deposits are shown to have commonly formed in second- and third-order structures in convergent tectonic settings. Although their paper is an overview, much specific deposit information is introduced that will help the explorationist.

Three other papers are concerned with epigenetic gold-bearing lodes in Alaska. Two of these discuss the auriferous ore settings in central- and southwestern Alaska, where data from fissure-type veins and stockwork systems are interpreted as showing distinct genetic relationships with magmatism. In a paper on precious metals associated with Late Cretaceous-early Tertiary igneous rocks of southwestern Alaska, Bundtzen and Miller (1997) describe the deposits in the Kuskokwim mineral belt and define a metallogenic model for the development of the gold-silver-polymetallic deposits of the region. This paper is an excellent descriptive summary of an underexplored region in Alaska that has recently been the focus of widespread exploration efforts, with recent exploration success at Donlin Creek. With the discovery and development of the Fort Knox deposit during the past few years, there has been a boom in exploration and development in the Yukon-Tanana terrane in east-central Alaska and adjacent Yukon Territory. Recent exploration successes at the True North and Stone Boy projects have highlighted the need for reassessment of exploration models. The magmatic origin for mid-Cretaceous gold systems in this area is explored and discussed in the paper by McCoy, Newberry, Layer, DiMarchi, Bakke, Masterman, and Minehan (1997). The authors integrate new 40Ar/39Ar ages with fluid inclusion and stable isotope data to support a model in which low-salinity, CO2-rich, gold-bearing fluids were derived from the evolving magmas of host intrusions.

The paper by Gray, Gent, Snee, and Wilson (1997) describes the geologic and geochemical setting of epithermal Hg-Sb veins of southwestern Alaska and epithermal gold veins of the Alaska Peninsula and the Aleutian Islands. These regions represent parts of the state where shallow crustal rocks are still preserved and are therefore favorable for epithermal ore deposits. New geochronologic data from the Hg-Sb vein deposits temporally link ore formation to Late Cretaceous magmatism. Significant precious metal exploration targets may exist at depth in these systems, with Au-As-W-rich mineralization occurring below exposed Hg-Sb ores. Perhaps more intriguing, from the standpoint of exploration, is the potential for large epithermal lode gold systems associated with Tertiary volcanic rocks on the Alaska Peninsula. Gray and the others forward the hypothesis that the gold-bearing systems may be associated with arc-related Cu porphyry systems. Between the remoteness of the region described in this paper and the extensive magmatic activity of the Aleutian arc, the potential for discovery of significant new ore systems is high.

The voluminous information on Alaskan volcanic-genetic massive sulfide deposits is brought together in the paper by Newberry, Crafford, Newkir, Young, Nelson, and Duke (1997b). Spatially distributed throughout much of Alaska, such deposits provide exciting exploration opportunities for precious and base metals. Past development of Late Cretaceous, Tertiary Cyprus-type, and Besshi-type ores characterizes much of the Prince William Sound area. The Late Triassic belt of mainly kuroko-type systems within rocks of the Alexander terrane in southeastern Alaska and British Columbia includes the huge Windy Craggy deposit and the extremely precious metal-rich Greens Creek ores. Early Paleozoic massive sulfides in the southern part of southeastern Alaska have been the focus of consistent industry attention during the past few years, and middle to late Paleozoic ores of the Ambler district in northwestern Alaska are again being evaluated. The paper by Newberry and the others describes and catalogs these deposits in addition to presenting interesting models for exploration.

Young, St. George, and Bouley (1997) address the tectonic association of porphyry copper occurrences through time in Alaska. Over the geologic history of the state, the authors identify ten distinct episodes of porphyry copper formation. Computer-generated palinspastic reconstructions are used to place these episodes in appropriate tectonic settings. The most abundant and the most economically significant occurrences are associated with Cretaceous intermediate igneous rocks. In the paper on molybdenum porphyry occurrences, Ashleman, Taylor, and Smith (1997) present the most detailed geologic description to date on Quartz Hill, one of the largest porphyry molybdenum deposits in the world. They tie a detailed understanding of the local deposit geology to the current models of porphyry systems to develop an improved genetic model for Quartz Hill. Development of such a local
model has been a long-term problem, because Quartz Hill shows features characteristic of both typical subduction-related ore systems and Climax-like, rift-related porphyry bodies.

The paper on skarn deposits of Alaska by Newberry, Allegro, Cutler, Hagen-Levelle, Adams, Nicholson, Weglarz, Bakke, Clautice, Coultier, Ford, Meyers, and Szumigala (1997a) describes over 300 skarn deposits and occurrences throughout Alaska. This paper is an extensive compilation of published material as well as recent research by the authors. As an interesting exploration guide, the authors suggest that although the host terrane seems to have little influence on the type of skarn, it may influence pluton composition, which will in turn control the skarn oxidation state. Additionally, Newberry and the others forward a model whereby the metals are derived from the plutions. After presenting all their descriptions and data, the authors point out how pluton characteristics should be used in skarn exploration.

Mafic and ultramafic complexes account for the production and existing resources of platinum-group elements, asbestos, and iron in Alaska. In the paper on mineral occurrences associated with these complexes, Foley, Light, Nelson, and Harris (1997) classify these igneous rock types based upon age, lithology, tectonic setting, structural and petrologic features, and metallogeny and identify five distinct types of related ore deposits. For the precious and base metal explorationist, this paper will provide some intriguing ideas for targets, since many of the platinum-group element placer and lode deposits also have yielded by-products of gold, silver, and copper.

Tin has not received the same attention that precious metals have in Alaska; however, Hudson and Reed (1997) forward the suggestion, based upon their geologic models, that under the right economic conditions, the state could be a significant producer of tin. They describe tin deposits associated with placers, veins, skarns, and greisens. Their optimistic view of the potential for significant discovery of tin is based upon the link between widespread Middle Cretaceous crustal melting in central and western Alaska and their new recognition of a broad regional tin belt.

Uranium, thorium, and rare metal deposits are uncommon in Alaska, but minor production of uranium has occurred from Bokan Mountain, in southeastern Alaska. In the paper on rare metal deposits, Thompson (1967) describes the igneous-hosted uraniumiferous Bokan Granite Complex and the sedimentary-rock-hosted Death Valley deposit on the Seward Peninsula. Although the economic outlook for uranium is bleak, this paper presents some important geologic characteristics of unique mineral deposits that may provide economically valuable minerals in the future.

The metallic minerals industry has figured significantly in the economics of Alaska and the future looks bright, but few all-encompassing geologic references are available that detail the numerous and varied mineral deposit types of the state. The lack of a comprehensive, up-to-date reference on the economic geology of Alaska has spurred the idea of this monograph. Such an effort was deemed timely given the resurgence of exploration and mining in the 1980s and 1990s, both in the state and internationally. Three years of work has culminated in this volume.

This monograph is a team effort representing the work of 48 authors and some 35 Economic Geology reviewers, each of whom devoted much free time to this project. In addition, various companies and organizations have generously contributed money to help defray printing costs. The contributors include Cominco Exploration, Cyprus Metals, Echo Bay Mines, Kennecott Exploration, Placer Dome U.S., Inc., and Sealaska Corporation. We thank the numerous people and companies who have been connected with this project.

We hope the reader will find this to be a useful volume on the geology of Alaska’s mineral deposits. We are excited about what the future holds for the development of mineral resources in Alaska. Clearly, a sound knowledge of the economic geology of Alaska’s mineral deposit types is integral to successful exploration and development of these resources.

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Metallogenic Evolution of Alaska

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Abstract

Lithotectonic terranes that are now the northwestern corner of North America record more than 500 m.y. of ore-forming processes. Almost all of Alaska’s mineral deposits older than 150 Ma formed in oceanic environments in blocks of oceanic crust, island arcs, or isolated continental fragments distant from North America or in platforms and basins adjacent to the Paleozoic North American continental margin. Most middle Cretaceous and younger ore systems, especially those concentrated in the southern part of the state, are associated with processes attendant to terrane accretion. Hydrothermal activity and commonly related magmatism were principally products of oceanic plate subduction beneath the southern Alaska continental margin. Few significant lode deposits in Alaska are postaccretionary, orogenic systems that are clearly unrelated to Mesozoic and Cenozoic plate convergence.

Late Proterozoic through Silurian polymetallic volcanogenic massive sulfide deposits, some broadly contemporaneous with Fe-Cu-Au skarns, are the oldest recognized major mineral deposits in Alaska. These deposits were formed during submarine-arc magmatism distant from the North American continent and are now located in rocks of the accreted Alexander terrane in the southernmost part of southeastern Alaska.

Shale- and carbonate-hosted base metal deposits and polymetallic volcanogenic massive sulfide deposits developed along the North American continental shelf in the Devonian and Carboniferous. Extension and probably rift-related volcanism along the continental margin were coeval with Antler-Ellsersian orogenesis landward on the craton. Resulting submarine hydrothermal activity formed the mineral deposits now exposed in rocks of the Arctic Alaska terrane in the western and central Brooks Range. They include stratiform, shale-hosted bodies such as Red Dog, massive syngeneic barite, carbonate-hosted copper systems such as Ruby Creek, and the volcanogenic massive sulfide occurrences of the Ambler district. The late Paleozoic continental margin strata of the Yukon-Tanana terrane, where exposed in central and southeastern Alaska, contain additional volcanogenic massive sulfide bodies that may be of similar origin.

Triassic rifting along the east side of the Alexander terrane, still distal to North America, was responsible for a third episode of polymetallic volcanogenic massive sulfide formation. Resulting deposits include Greens Creek, in the northern part of southeastern Alaska, and Windy Creek, in adjacent British Columbia. By the Late Triassic, the Alexander terrane was amalgamated with the Wrangellia, Peninsular, and northern Taku terranes into the Wrangellia superterrane. A second, probably unrelated Triassic rifting event along the superterrane led to extrusion of thick subaerial basalt flows within the Wrangellia terrane. These basalts served as the metal source for Kennecott-type copper deposits during terrane accretion to the craton later in the Mesoic.

Jurassic arc magmatism in the Pacific basin included formation of a series of mineral deposits in terranes that were obducted onto, or accreted to, western Alaska during a period of 100 m.y. Podiform chromite bodies formed in ultramafic plutonic rocks that were later obducted in the Brooks Range and Ruby geanticline as parts of the Angayucham terrane and formed part of the Talkeetna arc in the Peninsular terrane that is now part of south-central Alaska. Coeval volcanism in the Talkeetna arc was characterized by many small but widespread metalliferous events and the formation of at least one significant Jurassic volcanogenic massive sulfide system at the Johnson River prospect. Arc magmatism that formed the Goodnews and Togiak terranes included crystallization of Fe-, Ti-, and Pt-rich zoned ultramafic bodies. During the Quaternary, erosion of bodies in the former terrane led to major placer platinum accumulations that represent the largest resource of the metal in the United States.

Middle to Late Cretaceous terrane accretion and magmatism were associated with widespread metalliferous events. Copper porphyries and Fe-Cu-Au-bearing skarns formed in rocks of the Wrangellia terrane and in rocks of the inboard Gravina flysch basin soon after their accretion along south-central Alaska and were coeval with continuing subduction along the southern margin of these terranes. The associated thermal event probably also drove fluid circulation that led to deposition of Kennecott-type copper ores in litoral to supralittoral carbonate units above the Triassic rift basalts of the Wrangellia terrane. In the Gravina flysch basin in southeastern Alaska, middle Cretaceous arc magmatism included development of the Kluwan-Duke belt of Fe-rich, Alaska-type zoned ultramafic bodies. Late Cretaceous arc magmatism in southwestern Alaska, also inboard of the accreted Wrangellia superterrane, is temporally associated with formation of cinnabar-bearing epithermal lodes and Au-rich volcanoplutonic complexes. Farther north, Albian gold veins in the Seward and Arctic Alaska terranes could be products of extensional events in compressional orogens or could be the result of simple, broad-scale crustal thinning. In contrast, early Late Cretaceous gold veins in the Yukon-Tanana terrane show a close genetic association with subduction-related plutons that were likely derived from the underplating of Gravina flysch. Late Cretaceous extensional magmatism caused emplacement of tin granites on the Seward Peninsula.

Collisional tectonics continued to direct Alaskan mineral deposit formation in the Cenozoic. Plate conver-
gence and associated subduction led to the widespread development of Alaska's productive mesothermal gold vein systems throughout the southeastern and south-central fore arc. Metamorphic fluid flow, in many cases aided by changing Eocene plate motions in the Pacific basin, resulted in lode gold formation in the Chichagof district, the Juneau gold belt, and the Willow Creek district and across the Kenai-Chugach mountain range. Beginning in the late Eocene, growth of the Mesik and Aleutian arcs in southwestern Alaska was associated with the formation of Cu-Mo porphyry bodies and related epithermal gold vein occurrences. In contrast to collision-driven ore genesis, localized late Oligocene and early Miocene extension in southeastern Alaska included crystallization of the Quartz Hill molybdenum porphyry and formation of Zn-Pb and tin skarns in the Groundhog basin area.

Introduction

The Alaska cordillera is characterized by a diverse and complex metallogenic history reflecting pre-, syn-, and postaccretionary tectonic events within the various lithotectonic terranes that now compose the northwestern corner of the North American continent (Fig. 1). During the past 20 years, the development of concepts of plate tectonics has led to significant advances in understanding the geologic evolution of Alaska (Plafker and Berg, 1994) and the recognition that much of Alaska comprises fault-bounded crustal fragments or terranes (Fig. 2). This understanding allows for a revised explanation of the spatial distribution of mineral resources. Improvements in isotopic dating methods have increased our knowledge of the temporal distribution of Alaska's ore deposits. The aim of this paper is to outline the relationships between the growth of Alaska and the Proterozoic to Quaternary formation of Alaska's major mineral deposits.

Numerous tabulations of Alaska's mineral deposits have been published by various workers at the U.S. Geological Survey (Cobb and Kachadoorian, 1961; Berg and Cobb, 1967; Cobb, 1973; Noldeberg et al., 1987). Descriptive studies of major mineral deposits in northern Alaska were included in a special issue of Economic Geology (Einaudi and Hitzmann, 1956), and a summary of the metallogeny of southern Alaska was completed by Goldfarb et al. (1987). This paper focuses on the temporal development of Alaska's mineral deposits. The detailed spatial and genetic characteristics of each major ore deposit type are the subjects of subsequent chapters of this monograph. Dawson et al. (1992) apply a similar approach to the description of the metallogeny of the adjacent Canadian Cordillera.

Mineral Deposit Types and Their Spatial Distribution

Ore formation in oceanic settings

Many of Alaska's significant mineral deposits (Table 1) formed in oceanic settings, both within and distal to the continental margin, subsequent to initial opening of the Pacific Ocean at about 700 Ma. These include late Paleozoic slate-hosted base metal deposits (Schmidt, 1967a), volcanogenic massive sulfide deposits of various ages (Newberry et al., 1997a), and iron, chromium, or platinum-group element (PGE) enrichments in Jurassic island-arc rocks (Foley et al., 1997).

The stratiform, slate-hosted deposits of the eastern Brooks Range, including the world's largest zinc deposit at Red Dog, developed during Carboniferous rifting and formation of restricted shale-filled basins adjacent to North America. Carbonate-hosted copper deposits formed during the same hydrothermal episode in adjacent limestone units and appear similar in origin to Irish base metal deposits (Schmidt, 1977b). Polymetallic volcanogenic massive sulfide deposits are widespread in the Devonian to Mississippian continental margin rocks occurring within the Brooks Range, east-central Alaska, and southeastern Alaska. These deposits also developed farther from North America and now occur throughout rocks of the accreted Wrangellia superterrane (formed by preaccretionary amalgamation of the Wrangellia, Alexander, Peninsular, and northern Taku terranes) that rims southern Alaska. Examples include pre-Devonian deposits on southern Prince of Wales Island, Greens Creek and other Triassic deposits distributed along the length of the Alexander terrane, and the Jurassic Johnson River deposit west of Cook Inlet. In addition, Fe- and Cu-rich Besshi and Cyprus deposits are associated with Late Cretaceous and early Tertiary mafic volcanic rocks in the Prince William Sound region.

Podiform chromite deposits are in Jurassic ultramafic rocks obducted onto sedimentary rocks that now compose the Brooks Range, Ruby geanticline, and Chugach-Kenai Mountains. At Goodnews Bay, in southwestern Alaska, chromite and magnetite in dunite of an accreted Jurassic arc sequence are the source for significant placer PGE.

Ore formation in synaccretionary to postaccretionary settings

Vein deposits: Mesothermal and igneous-related gold vein systems and associated placers have long been the most widely sought and productive mineral deposit types in Alaska. Mesothermal gold-bearing quartz veins are widespread in metamorphic rocks throughout the state (Goldfarb et al., 1997). Deposits on the western edge of the Coast Mountains near Juneau, on Chichagof Island, and in the Kenai, Chugach, and Talkeetna Mountains are genetically related to thermal events along the early Tertiary convergent margin of southern Alaska. Similarly, those of the Yukon-Tanana upland in the east-central part of Alaska are associated with subduction-related processes, though they are of middle Cretaceous age (McCoy et al., 1997). Middle Cretaceous gold deposits of the Nome district on the Seward Peninsula and of the southern Brooks Range (Goldfarb et al., 1997) are, on the other hand, less clearly related to convergent margin tectonism, although lithospheric melting above a subducting slab cannot be ruled out in either case. Late Cretaceous gold deposits of the Kuskokwim basin in southwestern Alaska apparently represent more classic pluton-related vein types that developed during inboard-arc (or back-arc) magnetism, with some characteristics similar to those of the Colorado mineral belt (Bundtzen and Miller, 1997). The limited abundance of fluorite, tellurides, and adularia; the common presence of polymetallic veins; and the less alkaline nature of many of the gold-hosting igneous rocks in southwestern Alaska are, however, notable differences from many of the alkalic-type epithermal deposits of the Rocky Mountain region.
Because most of Alaska's outcrops are relatively deep crustal rocks, significant epithermal vein systems are recognized only in shallow crustal rocks of the Kuskokwim basin and the Alaska Peninsula (Gray et al., 1997). In the Kuskokwim basin, cinnabar- and stibnite-bearing quartz veins, perhaps distal parts of the Au-rich, pluton-related hydrothermal systems, were Alaska's only past mercury producers. The only epithermal gold mined in Alaska has come from Cenozoic veins on the Shumagin Islands, 40 km east of the Alaska Peninsula, where it is associated with the Aleutian volcanic arc.

Porphyry and skarn deposits: Undeveloped porphyry copper occurrences are scattered throughout Alaska (Young et al., 1997). They include small Devonian Cu-bearing bodies in the eastern Brooks Range, middle Cretaceous copper porphyries in the Wrangell Mountains and the Au-rich Pebble Copper porphyry at the north end of the Alaska Peninsula, and Tertiary copper and molybdenum porphyry deposits on the Alaska Peninsula and near Glacier Bay. In contrast to these magmatic arc-related porphyry bodies, the world-class Quartz Hill molybdenum porphyry in southeastern Alaska (Ashleman et al., 1997) is more closely associated with extensional tectonism.

Calcic Fe-, Cu-, and/or Au-rich skarns are recognized adjacent to Ordovician and Cretaceous plutons on Prince of Wales Island, Cretaceous porphyries of the Wrangell Mountains, and Cretaceous arc rocks of east-central and southwestern Alaska (Newberry et al., 1997b). Zinc-lead skarns developed in association with Devonian porphyry systems of the eastern Brooks Range and in carbonate rocks of the Farewell and Peninsular terranes during Paleocene arc magmatism.

Other deposit types: A number of other significant mineral deposit types occur locally. Carbonate-hosted Kennecott-type copper deposits probably formed during Mesozoic accretion.
of the Wrangellia terrane (MacKevet et al., 1997). Large Mississippi Valley-type deposits have not been identified in Alaska, but Schmidt (1997b) suggests that numerous, poorly studied Zn-Pb occurrences in east-central and southwestern Alaska indicate those areas might be favorable for future discovery of economic deposits of that type. Perhaps a phase of extension during a period of subduction-related magmatism in southeastern Alaska led to middle Cretaceous intrusion of Fe-rich, Alaska-type zoned ultramafic complexes along and near the Gravina flysch belt (Foley et al., 1997). Subsequent middle Tertiary transform motion along the continental margin of the Alexander Archipelago resulted in emplacement of gabbroic Ni-Cu bodies, including the Brady Glacier deposit. Uranium resources are associated with an enigmatic group of Jurassic peralkaline intrusive bodies on Prince of Wales Island and occur in a Tertiary sandstone-hosted deposit on the Seward Peninsula (Thompson, 1997). Tin-bearing veins, greisens, and related placers are associated with Cretaceous and early Tertiary plutons in the Ruby geanticline, Seward Peninsula, and Yukon-Tanana upland and with a magmatic arc in the Alaska Range-Kuskokwim Mountains (Hudson and Reed, 1997). In many cases, the Sn-bearing occurrences may be related to 20-m.y.-old magma systems that evolved from originally more calc-alkaline, subduction-related melts.

**Alaska's Metallogenic Episodes**

**Pre-Devonian**

Late Proterozoic and early Paleozoic strata along the western margin of North America record a passive pre-Devonian continental margin now inboard of subsequently accreted allochthonous terranes. Pre-Devonian sedimentary units in northern Alaska represent a part of the North American mio-geocline (Moore et al., 1994). Carbonate-shelf to deep-marine slope sedimentary strata, now exposed in the Brooks Range and Seward Peninsula, were deposited along the pas-
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Accreted Rocks of Southern Alaska Fore Arc

Accreted Arcs and Related Rocks of Western Alaska

EXPLANATION

Marine basalts and cherts

Intraoceanic arc rocks

Continental margin shelf and slope deposits

Rift volcanic rocks

Clastic basin overlap assemblages

Continental crystalline basement rocks

Melange

Estimated age of terrane amalgamation

FIG. 2. Temporal history of amalgamation and accretion for major terranes in Alaska. See Figure 1A for abbreviations of terranes.

The only mineral deposits found in Alaska that certainly are pre-Devonian in age occur in allochthonous rocks of Prince of Wales Island in the southernmost part of the southeastern Alaska panhandle (Fig. 3). Host rocks for precious metal-bearing Cu- and Zn-rich volcanogenic massive sulfide deposits, now part of the Alexander terrane, reflect two episodes of Late Proterozoic through Silurian submarine-arc volcanism in an intraoceanic region far south (?) of the present craton (Plafker and Berg, 1994). Most deposits, including Niblack, Khayyam, Stumble-On, and Copper City, are in rocks of the Late Proterozoic and Early Cambrian (?) Wales Group. A few occurrences, including those at Trocadero Bay, are hosted by units of the Early Ordovician to Early Silurian Descon Formation (Newberry et al., 1997a). Both the Wales Group and Descon Formation consist of felsic to mafic volcanic units and shallow-marine sedimentary rocks. Many of the volcanogenic massive sulfide deposits yielded only minor copper, gold, and silver in the early 1900s, but recently they have undergone consistent mineral exploration. Although the deposits are pre-Devonian in age, it was not until more than 300 m.y. later that they reached their present location along the Alaskan continental margin during accretion of the Alexander terrane. Rocks of the Alexander terrane correlate with those of the Descon Group have been recognized in the northern part of southeastern Alaska and in northwestern British Columbia (Norford and Mihalyzuk, 1994) and indicate an extensive tract favorable for the occurrence of early Paleozoic volcanogenic massive sulfide deposits.

Lenses of barite, interlayered with dolomite, occur within marble of the Wales Group at the Lime Point prospect (Twenhofel et al., 1949). The lenses may be a distal part of Cambrian or older volcanogenic hydrothermal systems. Barite, however, is rarely found in Precambrian Cu-Zn volcanogenic systems, perhaps because of low barium solubilities under conditions hypothesized to be relatively alkaline (Lydon, 1988). The relation between the Cu-Zn volcanogenic massive sulfide deposits and the barite is therefore problematic.

Middle Ordovician to Early Silurian diorite to trondhjemitic intrusions on southern Prince of Wales Island have been interpreted to be coeval with volcanic-arc rocks of the Descon Formation (Gehrels and Saleeby, 1987). Copper- and Au-rich iron skarns, now exposed on the Kasaan peninsula, formed in limestone and calcareous siltstone near Ordovician sills and
The relationship between the Sn- and base metal-rich magmatic systems is uncertain. The metasomatosic systems have affinities with typical Cu-Mo-rich continental margin porphyries (Newberry et al., 1986b) and have a U-Pb age of 402 
\[ \pm 8 \text{ Ma (Dillon et al., 1980). U-Pb dating of five of the peraluminous granites, summarized in Moore et al. (1994), indicates an age range between 357 and 380 \pm 10 \text{ Ma. It is therefore possible that the older, base metal systems were products of the Ellesmerian contractional event, whereas the younger, Sn-rich systems mark the onset of subsequent rift-related tectonics suggested to have commenced toward the end of the Devonian (Einaudi and Hitzman, 1986). In support of this, Dillon et al. (1987) hypothesized that Pb isotope data from the peraluminous igneous rocks suggest crustal melting during regional extension. The peraluminous granites have extensional trace element signatures and are associated with basaltic and gabbroic dikes, further supporting an extensional origin (Rainer Newberry, written commun., 1995). Nelson et al. (1993) argued, however, that Nd isotope data indicate a continental margin magmatic arc.}

The onset of possibly rift-related, Late Devonian extension within the sedimentary rock sequences of the Arctic Alaska terrane triggered a widespread, perhaps 100-m.y.-long period of base metal-rich ore deposition in northern Alaska. Shale-hosted Zn-Pb-Ag and associated barite, chert-hosted barite, carbonate-hosted copper, and volcanogenic Cu-Zn deposits formed across much of what is now the western and central Brooks Range during the latter half of the Paleozoic (Newberry et al., 1997a; Schmidt, 1997a, 1997b). The deposits formed on carbonate platforms and in shale basins along a south-facing continental margin shelf-platform sequence that began to develop during Late Devonian extension (Einaudi and Hitzman, 1986; Moore et al., 1994). Passive margin sedimentation, regional subsidence, and opening of the Angayucham basin continued for more than 200 m.y. (Moore et al., 1994). Associated sea-floor volcanism and basin dewatering along the margin led to the formation of both syngenetic and epigenetic ore deposits early in this interval.

Sedimentary-basin development during Mississippian and Pennsylvania extension resulted in Zn-Pb-Ag massive sulfide deposition within carboniferous shale and, less commonly, within chert. The most significant of these deposits is Red Dog, containing measured reserves of 55.2 million metric tons (Mt) grading 18.4 percent Zn, 5.5 percent Pb, and 93 g/t Ag (Bundtzen et al., 1994); a newly discovered deeper ore zone in the lowermost of three thrust plates at Red Dog, termed the Aqgaluk orebody, contains an additional 76 Mt grading 13.7 percent Zn, 3.6 percent Pb, and 66 g/t Ag (Kulas, 1996). Other examples include the nearby Lik deposit (Forest, 1983) and the Drenchwater occurrence, about 150 km east of the Red Dog deposit (Nokleberg and Winkler, 1982; Werdon, 1995). Most of these deposits are syngenic, as evidenced by laminated sulfides, vent fauna, monomineralic banding, resemented sulfide conglomerates, and associated bedded barite (Young, 1989). Multiple-vein episodes and breccia developments, silicification fronts, and replacement textures indicate that ore deposition continued subsequent to diageneis at Red Dog (Young, 1989). Schmidt and Zierenberg (1987) suggested that the massive Red Dog orebody, representing the largest known Phanerozoic Zn-Pb-Ag-
Table 1. Significant Mineral Occurrences of the Alaskan Cordillera

<table>
<thead>
<tr>
<th>Mineral deposit</th>
<th>Deposit type</th>
<th>Host terrane</th>
<th>Ore metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Devonian</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Khanyam-Stumble-On</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Cu</td>
</tr>
<tr>
<td>2. Copper City</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Cu</td>
</tr>
<tr>
<td>3. Niblock</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Cu</td>
</tr>
<tr>
<td>4. Trocadero Bay</td>
<td>VMS</td>
<td>AX</td>
<td>Cu</td>
</tr>
<tr>
<td>5. Lime Point</td>
<td>VMS (?)</td>
<td>AX</td>
<td>Ba</td>
</tr>
<tr>
<td>6. Kasaan Peninsula district</td>
<td>Fe skarn</td>
<td>AX</td>
<td>Ag, Au, Cu, Fe</td>
</tr>
<tr>
<td>7. Salt Chuck</td>
<td>Magnatic</td>
<td>AX</td>
<td>Ag, Au, Cu, Pd</td>
</tr>
<tr>
<td>8. Bug</td>
<td>Porphyry</td>
<td>AX</td>
<td>Ag, Cu, Mo</td>
</tr>
<tr>
<td>Devonian to Carboniferous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Victor-Genau</td>
<td>Porphyry skarn</td>
<td>AA</td>
<td>Ag, Au, Cu, Mo, Pb, Zn</td>
</tr>
<tr>
<td>10. Bear Mountain (?)</td>
<td>Porphyry</td>
<td>AA</td>
<td>Mo</td>
</tr>
<tr>
<td>11. Arrigetch Peaks-Mt. IgIpak-Ogulak</td>
<td>Sa skarn</td>
<td>AA</td>
<td>Sn</td>
</tr>
<tr>
<td>12. Red Dog</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>13. Lis</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>14. Drenchwater</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>15. Longview-Nimbusuk</td>
<td>Sedimentary barite</td>
<td>AA</td>
<td>Ba</td>
</tr>
<tr>
<td>16. Guny Ck</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>17. Wlioppes Ck</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>18. Story Ck</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>19. Kull-Yallee</td>
<td>Sediment hosted</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>20. Bully Creek</td>
<td>Carbonate hosted</td>
<td>AA</td>
<td>Cu</td>
</tr>
<tr>
<td>21. Omar</td>
<td>Carbonate hosted</td>
<td>AA</td>
<td>Cu</td>
</tr>
<tr>
<td>22. Arctic-Sus-Smucker</td>
<td>VMS</td>
<td>AA</td>
<td>Ag, Cu, Pb, Zn</td>
</tr>
<tr>
<td>23. Cagaryah</td>
<td>Sedimentary barite</td>
<td>FW</td>
<td>Ba</td>
</tr>
<tr>
<td>24. Reef Ridge district</td>
<td>MVT</td>
<td>FW</td>
<td>Pb, Zn</td>
</tr>
<tr>
<td>25. Bonifield district</td>
<td>VMS</td>
<td>YT</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>26. Trident Glacier</td>
<td>VMS</td>
<td>YT</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>27. Delta District</td>
<td>VMS</td>
<td>YT</td>
<td>Ag, Au, Cu, Pb, Zn</td>
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<tr>
<td>28. Shellabarger Pass</td>
<td>VMS</td>
<td>FW</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>29. Tracy Arm</td>
<td>VMS</td>
<td>YT</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>30. Sundum</td>
<td>VMS</td>
<td>YT</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>31. Sweetheart Ridge</td>
<td>VMS</td>
<td>YT</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>Late Triassic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32. Glacier Creek-Mt. Henry Clay</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Ba, Cu, Pb, Zn</td>
</tr>
<tr>
<td>33. Orange Point</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Cu, Zn</td>
</tr>
<tr>
<td>34. Greens Creek</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Pb, Zn</td>
</tr>
<tr>
<td>35. Fyrola</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Ba, Pb, Zn</td>
</tr>
<tr>
<td>36. Castle Island</td>
<td>Sedimentary barite</td>
<td>AX</td>
<td>Ba</td>
</tr>
<tr>
<td>37. Zarenbo Island</td>
<td>VMS</td>
<td>AX</td>
<td>Ag, Au, Cu, Pb, Zn</td>
</tr>
<tr>
<td>38. Motk Bay-EXL</td>
<td>VMS</td>
<td>TK (?)</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>Jurassic</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>39. Ilykrok Mt</td>
<td>Podiform chrome</td>
<td>AG</td>
<td>Cr</td>
</tr>
<tr>
<td>40. Avan Hills</td>
<td>Podiform chrome</td>
<td>AG</td>
<td>Cr</td>
</tr>
<tr>
<td>41. Mishiguk Mountains</td>
<td>Podiform chrome</td>
<td>AG</td>
<td>Cr</td>
</tr>
<tr>
<td>42. Shiluonacqak Mt</td>
<td>Podiform chrome</td>
<td>AG</td>
<td>Cr</td>
</tr>
<tr>
<td>43. Carlbow Mt</td>
<td>Podiform chrome</td>
<td>RB</td>
<td>Cr</td>
</tr>
<tr>
<td>44. Kiyuv Hills</td>
<td>Podiform chrome</td>
<td>RB</td>
<td>Cr</td>
</tr>
<tr>
<td>45. Mt. Hwarz</td>
<td>Podiform chrome</td>
<td>RB</td>
<td>Cr</td>
</tr>
<tr>
<td>46. Johnson River</td>
<td>VMS</td>
<td>PE</td>
<td>Au, Cu, Pb, Zn</td>
</tr>
<tr>
<td>47. Red Mt-Claim Point</td>
<td>Podiform chrome</td>
<td>PE</td>
<td>Cr</td>
</tr>
<tr>
<td>48. Bernard Mt</td>
<td>Podiform chrome</td>
<td>PE</td>
<td>Cr</td>
</tr>
<tr>
<td>49. Elhota</td>
<td>Podiform chrome</td>
<td>PE</td>
<td>Cr</td>
</tr>
<tr>
<td>50. Magnetite Island</td>
<td>Skarn</td>
<td>PE</td>
<td>Cu</td>
</tr>
<tr>
<td>51. Chitina Valley batholith</td>
<td>Porphyry</td>
<td>WR</td>
<td>Cu</td>
</tr>
<tr>
<td>52. Miles-Berg Creek</td>
<td>Skarn</td>
<td>WR</td>
<td>Ag, Au, Cu, Fe</td>
</tr>
<tr>
<td>53. Spirit Mountain</td>
<td>Mgmatric Cu-Ni</td>
<td>WR</td>
<td>REE, U</td>
</tr>
<tr>
<td>54. Bokan Mountain</td>
<td>Magnatic U</td>
<td>AX</td>
<td>REE, U</td>
</tr>
<tr>
<td>55. Doru Bay</td>
<td>Magnatic U</td>
<td>AX</td>
<td>REE, U</td>
</tr>
<tr>
<td>56. Goodness Bay</td>
<td>Zoned ultramatic</td>
<td>GD</td>
<td>PGE</td>
</tr>
<tr>
<td>57. Kenuk Mt (?)</td>
<td>Zoned ultramatic</td>
<td>TG</td>
<td>Fe, Ti</td>
</tr>
<tr>
<td>Mid-Cretaceous</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>58. Nome district</td>
<td>Mesothermal vein</td>
<td>SD</td>
<td>Au</td>
</tr>
<tr>
<td>59. Chandalar-Koyukok district</td>
<td>Mesothermal vein</td>
<td>AA</td>
<td>Ag, Pb, Zn</td>
</tr>
<tr>
<td>60. Independence</td>
<td>Polymetallic vein</td>
<td>SD</td>
<td>Ag, Pb, Sb</td>
</tr>
<tr>
<td>61. Onalak</td>
<td>Polymetallic vein</td>
<td>SD</td>
<td>Ag, Pb, Sb</td>
</tr>
<tr>
<td>Mineral deposit</td>
<td>Deposit type</td>
<td>Host terrane</td>
<td>Ore metals</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>62. Hanman Creek</td>
<td>Carbonate hosted</td>
<td>SD</td>
<td>Pb, Zn</td>
</tr>
<tr>
<td>63. Illinois Creek</td>
<td>Polymetallic vein (?)</td>
<td>RB</td>
<td>Ag, Au, Cu, Pb, Zn</td>
</tr>
<tr>
<td>64. Fairbanks-Circle-Fortymile-Hot Springs-Tolovana districts</td>
<td>Mesothermal vein, W skarn</td>
<td>YT</td>
<td>Au, W</td>
</tr>
<tr>
<td>65. Roy Creek</td>
<td>Magmatic U</td>
<td>WS</td>
<td>U, REE</td>
</tr>
<tr>
<td>66. Ruby district</td>
<td>Sn greisen</td>
<td>RB</td>
<td>Sn</td>
</tr>
<tr>
<td>67. Tofy district</td>
<td>Sn greisen</td>
<td>FW</td>
<td>Sn</td>
</tr>
<tr>
<td>68. Kennecott district (?)</td>
<td>Carbonate hosted</td>
<td>WR</td>
<td>Ag, Cu</td>
</tr>
<tr>
<td>69. Denali (?)</td>
<td>Carbonate hosted (?)</td>
<td>WR</td>
<td>Cu</td>
</tr>
<tr>
<td>70. Orange Hill-Bond Ck</td>
<td>Porphyry</td>
<td>WR</td>
<td>Cu, Mo</td>
</tr>
<tr>
<td>71. Baultoff-Carl Ck-Horsfeld</td>
<td>Porphyry</td>
<td>GN</td>
<td>Cu</td>
</tr>
<tr>
<td>72. Nachesma</td>
<td>Cu skarn</td>
<td>WR</td>
<td>Au, Cu</td>
</tr>
<tr>
<td>73. Zacley</td>
<td>Cu skarn</td>
<td>WR</td>
<td>Au, Cu</td>
</tr>
<tr>
<td>74. Pebble Copper</td>
<td>Porphyry</td>
<td>KH</td>
<td>Cu, Au</td>
</tr>
<tr>
<td>75. Khiwarm</td>
<td>Zoned ultramafic</td>
<td>GN</td>
<td>Fe, PGE, Ti</td>
</tr>
<tr>
<td>76. Sisuittuam</td>
<td>Zoned ultramafic</td>
<td>GN</td>
<td>Fe, PGE, Ti, V</td>
</tr>
<tr>
<td>77. Union Bay</td>
<td>Zoned ultramafic</td>
<td>GN</td>
<td>Fe, PGE, Ti, V</td>
</tr>
<tr>
<td>78. Duke Island</td>
<td>Zoned ultramafic</td>
<td>GN</td>
<td>Cr</td>
</tr>
<tr>
<td>79. Red Bluff Bay</td>
<td>Zoned ultramafic (?)</td>
<td>GN (?)</td>
<td>Cr</td>
</tr>
<tr>
<td>80. Junbo</td>
<td>Fe skarn</td>
<td>AX</td>
<td>Ag, Au, Cu</td>
</tr>
</tbody>
</table>

**Late Cretaceous**

| 81. Lost River | Sn greisen-skarn | SD | Be, F, Sn, W |
| 82. Kogarok    | Sn greisen-skarn | SD | Sn         |
| 83. Cape Mountain | Sn greisen-skarn | SD | Sn         |
| 84. Ear Mountain | Sn greisen-skarn | SD | Sn         |
| 85. Kasilof-Flat-Inoko districts | Plutonic Au | KK | Au, W |
| 86. Nixon Fork | Au skarn          | FW | Ag, Au, Cu |
| 87. Vinuak Mountian | Plutonic Au | KK | Au         |
| 88. Beaver Mountains | Plutonic Au | KK | Ag, Au, Cu, Pb |
| 89. Red Devil   | Epithermal vein   | KK | Hg         |
| 90. Cinnahe Creek | Epithermal vein  | KK | Hg         |
| 91. White Mountain | Polymetallic vein | FW | Hg         |
| 92. Kantiusha Hills district | Polymetallic vein, Cu skarn, breccia pipe | CH | Ag, Au, Cu |
| 93. Chulitna-Golden Zone | Polymetallic vein, Cu skarn, breccia pipe | CH | Ag, Au, Cu |
| 94. Mt. Estelle  | Plutonic Au       | KH | Au         |
| 95. Mudas       | VMS               | GC | Ag, Au, Cu, Zn |

**Paleocene and Early Eocene**

| 96. Taurus        | Porphyry                  | YT | Au, Cu, Mo |
| 97. Asaro         | Porphyry                  | YT | Au, Cu, Mo |
| 98. Bluff         | Porphyry                  | YT | Au, Cu, Mo |
| 99. Mosquito      | Porphyry                  | YT | Au, Cu, Mo |
| 100. Death Valley | Sandstone U               | SD | U         |
| 101. Circle district | Sn greisen              | YT | Sn         |
| 102. Linn Peak    | Sn greisen                | YT | Sn         |
| 103. Kasna Creek  | Skarn                      | PE | Ag, Au, Cu, Fe |
| 104. Crevice Creek | Skarn                      | PE | Ag, Au, Cu |
| 105. Romana Hills | Polymetallic vein         | KH | Ag, Au, Cu, Pb |
| 106. Yentna district | Magnatic Sn              | KH | Au, Sn     |
| 107. Coal Creek   | Magnatic Sn               | CH | Sn         |
| 108. Sleetat Mountain | Magnatic Sn              | KK | Sn         |
| 109. Valdez Creek district | Mesothermal vein       | KH | Au         |
| 110. Nuka Bay district | Mesothermal vein        | CC | Au         |
| 111. Moose Pass district | Mesothermal vein       | CC | Au         |
| 112. Hope-Sunrise district | Mesothermal vein  | CC | Au         |
| 113. Girdwood district | Mesothermal vein       | CC | Au         |
| 114. Port Wells district | Mesothermal vein      | CC | Au         |
| 115. Port Valdez district | Mesothermal vein     | CC | Au         |
| 116. Willow Creek district | Mesothermal vein    | PE | Au         |
| 117. Benes Bay district | Mesothermal vein     | WR | Au         |
| 118. Alaska Juneau-Treadwell | Mesothermal vein  | TK-CN | Au, Ag |
| 119. Sundum Chief | Mesothermal vein         | TK | Au         |
| 120. Chichagof district | Mesothermal vein    | CG-WR | Au         |
| 121. Bentson-Duchess | VMS                     | PW | Ag, Au, Cu |
| 122. Rua Cove      | VMS                       | PW | Cu, Fe, Zn |
| 123. Schlosser-Threeeman | VMS                  | PW | Ag, Au, Cu, Zn |
| 124. Ellamar (?)   | VMS                       | PW | Ag, Au, Cu, Zn |
| 125. Table Mountain | Porphyry                 | AA | Mo         |
bearing shale-hosted massive sulfide deposit, may have formed beneath an impermeable silicified barite cap. Leaching of clay minerals in the stratigraphically underlying Late Devonian to Early Mississippian shale during basin dewatering has been hypothesized as the source of the metals (Schmidt and Wedeen, 1993).

Unlike most of the other shale-hosted deposits, Red Dog contains a major barite resource that is spatially associated with the base metal-rich ore (Moore et al., 1986). Elsewhere in the western Brooks Range, massive syngenetic barite of Mississippian and, perhaps, Early Pennsylvanian age is distal to base metal-rich ores (Mayfield et al., 1979; Kelley et al., 1993). Approximately 50 Mt of barite is contained in seven barite occurrences; 60 percent of this resource is at the Longview deposit (Kelley et al., 1983). Most of the barite is in zones tens of meters thick and hundreds of meters long within bedded chert. Barite is locally associated with organic material and lacks base metal enrichments. Because these deposits are generally located in the same stratigraphic position as the Zn-Pb-Ag deposits, they probably are distal parts of the same hydrothermal systems. They may reflect fluids becoming more oxidized distal to vent areas, thus leading to the progressive shift from sulfide to sulfate deposition or nearby lower temperature sea-floor vents.

Disseminated sulfides in sandstone, and in veins and breccias cutting shale, delineate basin dewatering pathways that led to formation of the Carboniferous massive sulfides (Young, 1989). Such disseminated and vein breccia occurrences containing sphalerite, galena, and significant amounts of silver are common throughout the western Brooks Range. Occurrences at Ginny Creek (Mayfield et al., 1979), Story and Whoopee Creeks (Ellersieck et al., 1982), and Kady and Violee (Duttweiler, 1987) are hosted by Late Devonian to Early Mississippian clastic units.

Copper-rich strata-bound deposits were forming in stratigraphically lower platform carbonate rocks, probably at about the same time that Zn-Pb-Ag and barite deposits were originating in the basinal clastic rocks and cherts. The copper lodes include the Ruby Creek prospect (Hitzman, 1986), containing 91 Mt of rock averaging 1.2 percent Cu, and the Omar occurrence (Folger and Schmidt, 1986). Early diagenetic dolomitization of Devonian limestone host rocks was followed by deposition of massive, Co-rich pyrite that, in turn, was replaced by chalcopyrite and then bornite. The source of copper is uncertain. Although mineral deposition at Ruby Creek can be constrained only broadly between the Middle to Late Devonian age of the host rocks and the Middle Jurassic to Cretaceous Brookian deformation, Folger and Schmidt (1986) presented fossil evidence for a Devonian age of ore formation at Omar. A genetic connection, if any, between the carbonate-hosted copper and shale-hosted Zn-Pb-Ag deposits is uncertain. It is possible, however, that thermal perturbations associated with poorly understood continental margin extension and igneous activity in the Devonian (Dillon et al., 1986; Einaudi and Hitzman, 1986) may have initiated major fluid migration simultaneously in clastic basins and adjacent carbonate platforms.

Bimodal volcanism along the continental margin, a process likely related to rifting, was contemporaneous with formation of Devonian to Mississippian Zn-Pb-Cu volcanogenic massive sulfide deposits in rocks that now underlie the Ambler district of the southern Brooks Range. Spatial association between the deposits and rhyolitic units indicates a genetic connection. Occurrences in the district are estimated to contain more than 60 Mt grading 0.8 to 4.0 percent Cu, 2.6 to 6.8 percent Zn, 0.8 to 2.3 percent Pb, and 40 to 200 g/t Ag; more than half of this is hosted in the Arctic prospect (Hitzman et al., 1986). The presence of shallow-water fossils, abundant carbonate rocks, and possibly subaerial volcanic rocks supports sulfide deposition at relatively shallow-water depths above submarine vents (Hitzman et al., 1986). The sequence of bimodal volcanic rocks found in the Ambler district is discontinuously exposed for more than 400 km across the southern Brooks Range (Dillon, 1980). However, no additional signifi-

<table>
<thead>
<tr>
<th>Mineral deposit</th>
<th>Deposit type</th>
<th>Host termine</th>
<th>Ore metals</th>
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<tbody>
<tr>
<td>Mid-Enocene to Oligocene</td>
<td>Zn-Pb skarn</td>
<td>FW</td>
<td>Ag, Cu, Pb, Zn</td>
</tr>
<tr>
<td>126. Farewell</td>
<td>Sn skarn-replacement</td>
<td>YT</td>
<td>Sn, Ag, Pb, Zn</td>
</tr>
<tr>
<td>127. Groundhog Basin</td>
<td>Magnesite Ni-Cu</td>
<td>CG</td>
<td>Co, Cu, Ni</td>
</tr>
<tr>
<td>128. Brady Glacier</td>
<td>Porphyry</td>
<td>AX</td>
<td>Cu</td>
</tr>
<tr>
<td>129. Margerie Glacier</td>
<td>Cu skarn</td>
<td>AX</td>
<td>Ag, Au, Cu, W</td>
</tr>
<tr>
<td>130. Renski Glacier</td>
<td>Fe skarn</td>
<td>AX</td>
<td>Ag, Au, Cu, W</td>
</tr>
<tr>
<td>131. Alaska Chief</td>
<td>Mn skarn</td>
<td>AX</td>
<td>Mo</td>
</tr>
<tr>
<td>132. Nunatak</td>
<td>Porphyry</td>
<td>YT</td>
<td>Mo</td>
</tr>
<tr>
<td>133. Quartz Hill</td>
<td>Epithermal vein</td>
<td>PE</td>
<td>Au, Ag</td>
</tr>
<tr>
<td>134. Alaska-Apollo</td>
<td>Epithermal vein</td>
<td>PE</td>
<td>Cu, Mo</td>
</tr>
<tr>
<td>135. Shumagin</td>
<td>Porphyry</td>
<td>PE</td>
<td>Cu, Mo</td>
</tr>
<tr>
<td>136. Pyramidal</td>
<td>Porphyry</td>
<td>PE</td>
<td>Cu, Mo</td>
</tr>
<tr>
<td>137. Bee Creek</td>
<td>Porphyry</td>
<td>PE</td>
<td>Cu, Mo</td>
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<tr>
<td>138. Ivanof</td>
<td>Porphyry</td>
<td>PE</td>
<td>Cu, Mo</td>
</tr>
<tr>
<td>139. Mike</td>
<td>Epithermal vein</td>
<td>PE</td>
<td>Cu, Mo</td>
</tr>
<tr>
<td>140. Rex</td>
<td>Porphyry</td>
<td>PE</td>
<td>Au, Cu</td>
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Abbreviations for most host termene are listed in Figure 1A; also KK = the Cretaceous sedimentary rocks of the Kuskokwim basin, CH = the Chulitna termene of Junes et al. (1977). MVT = Mississippi Valley type, VMS = volcanogenic massive sulfide; (?) = uncertain age of deposit, deposit type, or host termene.
cant volcanogenic massive sulfide prospects are known outside the Amberl district.

Early Paleozoic rocks of the Seward Peninsula may have undergone a pre-middle Cretaceous tectonic history similar to that experienced by rocks of the southern Brooks Range. Strata of the Devonian and older Nome Group, which underlie much of the Seward Peninsula, were deposited in a continental margin platform environment and were subsequently exposed to at least one major period of rifting (Till and Dumoulin, 1994). Gamble and Till (1993) described one Zn-Pb-Ag deposit hosted by metamorphosed carbonate rocks of the Nome Group at Hanum Creek that hypothetically is a Paleozoic sedimentary exhalative deposit. The lack of association with a shale-rich basin, lack of recognition of any nearby volcanism or obvious feeder zones, and apparent lack of associated barite suggest that such a classification is far from certain. Moreover, Pb isotope data for galena from the Hanum Creek deposit are similar to data for Cretaceous magmatic-related deposits in northwestern Alaska (Church et al., 1985). Because late Paleozoic strata are not known on the Seward Peninsula (Till and Dumoulin, 1994), syngenetic Zn-Pb-Ag deposits like those in the Brooks Range are not likely targets.

The Ruby geanticline is a pre-middle Cretaceous uplift that trends diagonally across central Alaska, striking southwesterly from the southeastern edge of the Brooks Range (Fig. 1B). Lithologic and metamorphic similarities between sedimentary rocks of the geanticline and those of the southern Brooks Range have led to the suggestion that the Ruby geanticline is a counterclockwise-rotated (Putton, 1970) or clock wise-rotated (Tailleur, 1980) fragment of the southern Brooks Range. Unlike that part of the Brooks Range, however, base metal-rich deposits do not occur in the Ruby geanticline. If the geanticline is a geologic extension of the southern Brooks Range, the lack of felsic volcanic rocks is consistent with little sea-floor hydrothermal activity in that part of the continental margin.

Slightly prior to extension in rocks now composing the Brooks Range, a similar continental margin tectonic event occurred toward the south in rocks now in the Yukon. Rifting along the westernmost part of the miogeocline to form the Selwyn basin and its southern extension, the Kekihka trough, led to formation of Late Devonian sedimentary-rock-hosted Zn-Pb-Ag and barite deposits within local, fault-bounded, starved marine basins (MacIntyre, 1991). Post-Paleozoic right-lateral movement along the Tintina and Denali fault systems may have displaced some of the basinal strata westward into Alaska. Such a hypothesis has been argued by Bundtzen and Gilbert (1991) to explain the origin of the recently discovered Gagahar barite deposit in southwestern Alaska. The deposit occurs in Middle to early Late Devonian silstone and shale at the base of the Mystic sequence of the Farewell terrane along the south side of the Denali fault system. Its location indicates a second region within the Alaska basin. The large, shallow-hosted, base metal-rich mineral deposits. Small Zn-rich mineral occurrences in the Reef Ridge district in nearby parts of the Farewell terrane that are underlain by carbonate rocks (Schmidt, 1997b) may represent Mississippi Valley-type deposits that also formed during tectonism in the Selwyn basin.

Formation of Zn-Pb-Cu-rich volcanogenic massive sulfide deposits near this part of the continental margin occurred at roughly the same time that deposits were being formed slightly eastward in the Kekihka trough. Generally small Late Devonian to Mississippian volcanogenic massive sulfide deposits are scattered for more than 1,000 km along the southern part of the complexly deformed Yukon-Tanana terrane. The polydeformed metamorphic rocks of the Yukon-Tanana terrane that host the deposits would probably have been located outboard of the Selwyn basin, along the continental margin, during hydrothermal activity. As in the Brooks Range, the exact genetic relationship between the relatively coeval volcanogenic massive sulfide deposits of the Yukon-Tanana terrane in Alaska and the Canadian shale-hosted massive sulfide occurrences is uncertain. Lead isotope data indicate a similar lead source for both the shale-hosted and volcanogenic massive sulfide deposits (Church et al., 1987). Extensive and long-lived thrust faulting hindered reasonable palynostratic reconstruction of the ore-bearing Yukon-Tanana terrane fragments. Duke et al. (1984) favored genesis of the volcanogenic massive sulfide deposits during a continental margin rifting episode, which was perhaps responsible for the formation of Devonian and Mississippian shale-hosted deposits of the Selwyn basin and the eventual opening of the Mississippian to Permian Anvil ocean. Alternatively, Mortensen (1992) and Lange et al. (1993) preferred formation of such deposits during Devonian to Mississippian subduction, continental margin igneous-arc magmatism above a north- northeast-dipping subduction zone, which would have been located outboard of the rift basins. Metavolcanic and intrusive rocks that record this arc event have been dated at between 375 and 341 Ma (Mortensen, 1992).

These Yukon-Tanana terrane-hosted volcanogenic massive sulfide deposits in east-central Alaska, described in detail by Lange et al. (1993), are now distributed along the north side of the Denali fault system in rocks of a few small subterrains of the Yukon-Tanana terrane; sulfide-rich orebodies of the Bonnifield, Trident Glacier, and Delta districts are spread along a length of about 150 km. The pyrrhotite-dominated pods, lenses, and stringers are hosted by felsic intermediate volcanic flows and tuffs and metamorphosed marine sedimentary rocks. Lange et al. (1993) reported that the largest known sulfide body contains 18.1 Mt of 0.3 to 0.7 percent Cu, 1 to 3 percent Pb, 3 to 6 percent Zn, 34 to 100 g/t Ag, and 0.9 to 3.4 g/t Au. Additional Devonian-Mississippian Cu-, Pb-, and Zn-rich volcanogenic massive sulfide prospects continue to the east in the Yukon-Tanana terrane (including Kudz ze Kayah and Wolverine) and are products of the same volcanic episode. These occur along the south side of the Tintina fault system at the western edge of the Yukon (Johnston and Mortensen, 1994).

West of the Yukon-Tanana terrane deposits, other volcanogenic Cu-Zn bodies are hosted by marine sedimentary rocks spatially associated with submarine pillow basalts of the Mystic sequence in the Farewell terrane at Shellabarger Pass, central Alaska Range (Reed and Erbelein, 1972). Although basalts in the Mystic sequence are generally considered to be Triassic in age (Decker et al., 1994), Reed and Nelson (1977) present stratigraphic evidence for a probable Mississippian age for those at Shellabarger Pass. If the volcanogenic
massive sulfide occurrences are Mississippian in age, then they formed on the west side of the Selwyn and other continental margin basins prior to westward displacement of the Farewell terrane.

Recent redefinition of terranes in southeastern Alaska (Gehrels et al., 1992; McClelland et al., 1992; Rubin and Saleeby, 1992) indicates that middle Paleozoic rocks of the Yukon-Tanana terrane extend throughout much of the length of the panhandle. Massive lenses of Zn-Pb-Cu-bearing sulfide minerals containing significant amounts of silver and gold occur in a sequence of metapelite, quartzite, minor marble, felsic and mafic volcanic rocks, and granodioritic orthogneisses that are termed the Endicott Arm assemblage to the north, the Ruth assemblage in central southeastern Alaska, and the Kah Shakes sequence to the south. These possible Devonian to Mississippian occurrences include those at Tracy Arm, Sumdum, and Sweetheart Ridge, south of Juneau, and at Moch Bay and IXL, near Ketchikan. The largest of these, the Sumdum deposit, contains 24.2 Mt of 0.6 percent Cu, 0.4 percent Zn, and 9.3 g/t Ag (U.S. Geological Survey and U.S. Bureau of Mines, 1984).

The same type of late Paleozoic volcanogenic deposits are recognized farther to the east, in the Tulsequah district of northern British Columbia and the Barriere district of south eastern British Columbia. Although the British Columbia deposits are not hosted by rocks assigned to the Yukon-Tanana terrane, they may be products of the same continental margin magmatic event that impacted an adjacent terrane.

Triassic

No significant mineral deposits are known to have formed along the northwestern edge of North America from the time of the Devonian to Mississippian Antler orogeny to the end of the Triassic. Northern Alaska was the location of passive margin subsidence and sedimentation during this interval (Moore et al., 1994). Deformation of basinal strata within the Yukon-Tanana terrane occurred along the continental margin during Permian and Triassic time, but no major metallogenic events associated with this contraction are documented in Alaska.

Proterozoic through Devonian strata of the Alexander terrane remained near the paleoequator as part of an intraoceanic microcontinent from Devonian through Late Triassic time (Haeussler et al., 1992). Presence of a thick section of Triassic basal strata and associated bimodal volcanic rocks that unconformably overlie the Paleozoic strata indicates that the Alexander terrane was rifted during the early Mesozoic (Gehrels and Saleeby, 1987). The rift-related volcanism was responsible for a third, and the most economically significant,
Small deposits in the Triassic bimodal volcanic rocks now extend for about 400 km along the length of the Alexander terrane, from Windy Craggy, just north of the Alaska border, south to numerous small deposits in the Petersburg region (Fig. 5). The Windy Craggy deposit occurs near the contact between Triassic basalts and fine-grained clastic sedimentary rocks. It is estimated to contain more than 190 Mt of 1.6 percent Cu, 0.2 g/t Au, and 0.09 percent Co (Hoy, 1981). Windy Craggy differs from the other deposits in the belt in having low silver, lead, and zinc grades.

Most of the Late Triassic volcanogenic massive sulfide deposits consist of lenses of pyrite, pyrrhotite, sphalerite, galena, chalcopyrite, and/or barite that have elevated silver and gold grades. The Greens Creek deposit, near Juneau, is the most significant of these and was the largest silver producer in the United States in the early 1990s. It contains 12.5 Mt of ore grading 12.8 percent Zn, 4.0 percent Pb, 0.4 percent Cu, 456 g/t Ag, and 4.1 g/t Au (Bundtzen et al., 1994). During the 1960s and 1970s, 0.78 Mt of 90 percent barite (Bundtzen et al., 1994) was mined from massive lenses on Castle Island, the

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**Fig. 4.** Mineral deposits of Late Devonian and Mississippian age formed along the passive northwestern margin of the North American craton. Shale-hosted massive sulfide, carbonate-hosted copper, and Cu-Zn-rich volcanogenic massive sulfide deposits formed in the northern part of the Arctic Alaska terrane during probable rifting; small porphries and skarns in the southeastern part of the Arctic Alaska terrane are associated with arc magmatism; and polymetallic volcanogenic massive sulfide deposits developed in the Yukon-Tanana terrane during Carboniferous opening of the Anvil Ocean. Inferred tectonic configuration from Plahker and Berg (1984). See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.

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**Fig. 5.** Polymetallic volcanogenic massive sulfide deposits formed throughout the Alexander terrane during mostly Norian, rift-related volcanism within an intracratonic microcontinent. Extrusion of a thick sequence of subaerial and shallow-marine flood basalts in the adjoining Wrangellia terrane occurred in Carnian time. Inferred tectonic configuration from Plahker and Berg (1994), except that Taku terrane rocks have been hypothesized as a part of the superterrane. See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.
only barite mined in Alaska to date. The Zn-Pb-Cu-bearing volcanogenic massive sulfide bodies in southeastern Alaska are consistently hosted by fine-grained elastic units, mafic volcanic rocks, and metachlorite (Berg and Geybeck, 1980; R. Newberry, written commun., 1995). At Greens Creek, ore zones occur along the contact between black argillite and mafic flows and tuff (Crafford, 1989). The 40Ar/39Ar dating of hydrothermal mariposite from one small volcanogenic massive sulfide occurrence near Greens Creek indicates an age of 211 Ma for some of the sulfide deposition (Taylor et al., 1995). Gold-bearing quartz veins are common near some of the volcanogenic massive sulfide lenses at the southern end of the belt (Berg and Geybeck, 1980) and below the sulfide horizon at Greens Creek. It is likely that these gold systems reflect local remobilization from the volcanogenic massive sulfide deposits during later deformation and metamorphism.

By Late Triassic time, the Alexander terrane was amalgamated with the Wrangellia, Peninsular, and at least the northern part of the Taku terrane into the Wrangellia superterran and was located far from the present North American cratonic margin (Pflafler et al., 1989b). Tholeiitic basalts in the Wrangellia and Taku terranes (Pflafler et al., 1989a) further mark the onset of rifting events. Triassic volcanic rocks, which characterize the Wrangellia terrane, are dominated by the Nikolai Greenstone and are up to 6 km of subaerial and shallow-marine flood basalt. Such widespread volcanism could reflect regional rifting, back-arc spreading, or a mantle-plume event (Pflafler et al., 1994). The Nikolai Greenstone hosts numerous small copper deposits, and the overlying Late Triassic limestone hosts the world-class Kennecott-type copper orebodies of post-Jurassic age. Although the Carnian flood basalts were extruded within a few tens of millions of years of the Norian bimodal volcanic rocks of the Alexander terrane, a direct correlation between the two magmatic suites is unproven. Radiogenic isotopic signatures of the Wrangellia and Alexander volcanic rocks, however, have a great deal of overlap (Samson et al., 1990) and palaeomagnetic data suggest they were originally at about the same latitude (Haeussler et al., 1992).

Jurassic

Jurassic mineral deposits in Alaska developed in oceanic arc-trench environments at great distances from the North American continental margin (Fig. 6). Rocks with evidence for such arc activity now rim the interior of the state as mostly poorly exposed Paleozoic and early Mesozoic marine units. Jurassic arc-related sequences include the Angayucham terrane in northern Alaska, the Togjak and Yukon-Koyukuk arcs of western Alaska, and the Talkeetna and Chitina arcs of southern Alaska. These arcs, formed either on oceanic crust or on rifted continental fragments, may have resembled those now ringing the southwestern Pacific Ocean (Wallace et al., 1989). Geologic data indicate that subduction zones generally faced the continent toward which the arcs were migrating (Wallace et al., 1989). Representing part of the Pacific Ocean basin, the Yukon-Koyukuk arc and underriding Angayucham terrane collided with the Arctic Alaska terrane in Late Jurassic time; this event may have initiated the Brookian orogeny in northern Alaska (Mull, 1982; Box, 1985). This collisional event, continuing through at least the Early Cretaceous, was responsible for widespread blueschist facies metamorphism of underthrust rocks now composing most of the Brooks Range and the Seward Peninsula.

Arc magmatism produced podiform chromitite deposits in
early Middle Jurassic time in the Angayucham terrane, podiform chromite and volcanogenic massive sulfide deposits in late Early to early Middle Jurassic time in the Talkeetna arc, small iron skarns in the late Middle Jurassic in the Talkeetna arc, and copper porphyry, copper skarn, and magmatic Ni-Cu deposits in the Late Jurassic-Chitina arc. Magnetic events, perhaps products of local extensional episodes, also led to Middle Jurassic emplacement of PGE-rich, Alaska-type zoned ultramafic complexes in the Togia arc and Late Jurassic emplacement of U-rich bodies at the southern end of the Chitina arc.

Early Mesozoic arc volcanism took place in the Angayucham basin offshore of the Arctic Alaska terrane. Early Middle Jurassic crystallization ages from the event are recorded by ophiolites throughout the western Brooks Range. The volcanic and subjacent rocks were detached from the basin in the late Middle Jurassic and were obducted onto older continental crust of the Arctic Alaska terrane by the latest Late Jurassic (Wirth and Bird, 1992) as the Angayucham terrane, the uppermost allochthon in the present-day Brooks Range thrust belt. Dunite, harzburgite, and peridotite of these Tertiary ophiolites host podiform chromite occurrences containing anomalous PGE concentrations (Foley et al., 1997). An estimated 0.7 to 2.3 Mt of Cr₂O₃ is contained in 70 occurrences at Jiyork Mountain, Avan Hills, Misheguk Mountain, and Sinikstaneyak Mountain (Foley, 1992). Foley (1992) reported as much as 4.7 ppm Pd and 4.2 ppm Pt in selected chromitite samples. A number of smaller but similar chromite occurrences are at Caribou Mountain, Kiyuh Hills, Mount Hurst, and elsewhere throughout the Ruby geanticline. If the geanticline was a geologic extension of the southwestern Brooks Range (Patton, 1970), then Middle Jurassic chromite deposits in both the Brooks Range and Ruby geanticline have the same origin.

Fault-bounded blocks of Devonian through Jurassic marine sedimentary and volcanogenic rocks of the Goodnews terrane were subducted below and accreted to the northwestern edge of the Togia arc beginning in Early Jurassic time, perhaps offshore of the Eurasian continent (Box, 1985). As an arc-trench system developed, early Middle Jurassic gabbros and Alaskan-type zoned ultramafic bodies intruded rocks of the Goodnews terrane. The plutonic rocks are now exposed at Goodnews Bay in southwestern Alaska, about 150 km south of the mouth of the Kuskokwim River. Dunitic parts of this complex were subsequently eroded in the Quaternary and are the source for the Pt-rich placer deposits that represent the largest PGE resource in the United States (Foley et al., 1997). Studies of placer concentrates indicate that the PGE are concentrated in chromite and magnetite in the dunitic (Foley, 1992), but few lode occurrences have been found in the ultramafic mafic and ultramafic rocks. This means either that the PGE are very finely disseminated or that the source lodes have since been eroded (Mertic, 1976).

The Keniuk Mountain iron deposit, which has reserves of 2,200 Mt of 15 to 17 percent Fe, 2 to 3 percent TiO₂, and 0.16 percent P₂O₅ (Bundtzen et al., 1994), is located about 250 km east of the Goodnews Bay Pt-bearing rocks. The iron occurs in magnetite, which is 10.5 to 16.5 percent of the rock volume, in a magnetite-pyroxenite zone between pyroxenite and gabbro intrusive phases (Humble Oil and Refining Co., unpublished company report, 1959). The igneous complex, drilled in the late 1950s because of its aeromagnetic expression, and rocks of the surrounding Togia terrane are buried beneath till and alluvium of the Nushagak lowlands. Limited information from drill core suggests that this may be a zoned ultramafic body (Foley et al., 1997). The time of pyroxenite emplacement and associated iron ore formation is unknown, but a Middle Jurassic age seems likely. The Togia and Goodnews terranes were amalgamated into a single arc complex by that time, and the ultramafic bodies at Goodnews Bay and Keniuk Mountain could be the roots of the arc.

The rifted piece of microcontinent containing the Peninsular, Wrangellia, Alexander, and northern Taku terranes (the Wrangellia superterrane) migrated northward across the Pacific basin in Jurassic time. From Late Triassic (?) through Middle Jurassic time, plate subduction led to the development of the Talkeetna arc on deformed Paleozoic basement throughout the Peninsular terrane and in parts of the Wrangellia terrane (Plafker et al., 1989b). Andesitic tuffs, flows, and volcanic rocks of the Talkeetna Formation are the eruptive part of this intraoceanic arc. Mafic plutonic roots of the arc include layered gabbro-norite, peridotite, pyroxenite, and dunite that now form the informally named Border Ranges ultramafic-mafic complex. These arc-related rocks are exposed in a belt 1,000 km long and less than 20 km wide that extends from the Copper River to southwest of the Kodiak Islands along the contact between the Peninsular and Chugach terranes. Burns (1985) has interpreted the ultramafic-mafic complex as the fractional crystallization residuum of the magma that fed the Talkeetna arc. Newberry et al. (1986a) argue for a 180 to 200 Ma age for the mafic-arc rocks. The plutonic roots of the arc in the Peninsular terrane were likely obducted onto melange of the Chugach terrane during Cretaceous deformation associated with collision between the Wrangellia superterrane and the seaward Chugach terrane.

During the Early and early Middle Jurassic, subaqueous Talkeetna arc volcanism was accompanied by widespread, though generally economically insignificant, metaliferous hydrothermal activity in what are now the northern Alaska Peninsula, Talkeetna Mountains, and Chugach Mountains (Newberry et al., 1986a). On the west side of Cook Inlet, the Johnson River deposit (Steele, 1987) represents the only recognized significant volcanogenic massive sulfide system formed during this hydrothermal episode. Gold- and base metal-rich quartz stockworks cut volcanioclastic and associated marine sedimentary rocks that were already pervasively altered to an anhydrite-chlorite-sericite assemblage. Resources of 0.7 Mt grading 12.4 g/t Au, 9.18 percent Zn, and 0.97 percent Cu have been estimated at Johnson River (Rockingham, 1993). The discordant nature of the ore suggests that much of the original syngenetic mineral deposit has been remobilized.

Obducted dunite in the Border Ranges ultramafic-mafic complex contains pods, wisps, bands, and disseminated grains of podiform chromite. A total resource of 2.5 Mt of Cr₂O₃ is in 42 deposits hosted by the ophiolitic complex (Foyle et al., 1985). More than half of the resource is at Red Mountain, near Seldovia, which contains 1.4 Mt of material averaging 5 to 6 percent Cr₂O₃ and 0.1 Mt of material averaging more than 20 percent Cr₂O₃; the adjacent Windy River placer con-
tains 0.5 Mt of material averaging 1.33 percent Cr₂O₃ (Foley et al., 1985). The only chromite mined in Alaska, about 0.03 Mt of 40 percent Cr₂O₃ (Foley and Barker, 1985), came from Red Mountain and the adjacent Claim Point deposit.

Felsic to intermediate intrusive rocks make up the youngest and most voluminous part of the Talkeetna island arc. These rocks, recognized as the oldest part of the Alaska-Aleutian Range batholith, were emplaced between about 174 and 158 Ma along a length of more than 1,300 km, extending from the southern Alaska Peninsula northeast to the Talkeetna Mountains (Reed et al., 1983). No significant mineral deposits are known to be associated with this late Middle to early Late Jurassic igneous episode. Only a few small iron skarns, such as the Magnetite Island occurrence (Grantz, 1956), are recognized in Triassic sedimentary rocks adjacent to Jurassic plutons.

Immediately following the development of the Talkeetna arc, quartz diorite, tonalite, and granodiorite plutons of the Tonsina-Chichagof magmatic belt (Hudson, 1979) were emplaced along the southern margin of the Wrangellia and Alexander terranes between about 160 and 140 Ma (Roeseke et al., 1991). This belt now extends 800 km, from the north side of the eastern Chugach and St. Elias Mountains to central Chichagof Island. It reflects the roots of the Chitina arc, developed during north-to-northeast-directed subduction of the Chugach terrane below the Wrangellia superterrane (Plafker et al., 1989b). This magmatic episode might represent a Late Jurassic southeastward migration of Talkeetna arc magmatism.

A few small mineral deposits are associated with Late Jurassic magmatism. Copper porphyry prospects in granodiorite and quartz diorite and copper skarns in adjacent Late Triassic limestone are concentrated in the southwestern Wrangell Mountains, located about 40 km northwest of the Kennecott copper mines (Moift and Mertie, 1923). East of the Copper River and along the north side of the Chugach Mountains, ultramafic sills in the Chulitna arc contain concentrations of copper and nickel in massive lenses and disseminations of pyrite, pyrrhotite, pentlandite, and chalcopyrite (Herreid, 1970).

In the southernmost part of the Wrangellia superterrane, a peralkaline granite ring-dike complex was intruded into early Paleozoic metaplutonic and metasedimentary rocks on southern Prince of Wales Island between 167 and 151 Ma (Armstrong, 1985). Quartz- and albite-rich veins and pipes, emplaced between the igneous bodies and within fault zones, contain about 1 percent U₂O₅ and 3 percent ThO₂ (Thompson, 1997). Since 1957, intermittent mining of these U-Th deposits at Bokan Mountain has accounted for the only uranium mined in Alaska. In the Dora Bay area, located about 30 km north of Bokan Mountain, peralkaline intrusions probably of similar origin are enriched in rare earth elements (REE), yttrium (Barker and Mardock, 1990), and molybdenite (Philpotts et al., 1993).

The reason for emplacement of these U- and REE-enriched peralkaline rocks at the southern end of the Alexander terrane is uncertain. Their chemistry and ring-dike structure, both unique within the accreted terranes of the western cordillera, suggest emplacement in an extensional setting. The late Middle to Late Jurassic age constraint on this igneous event indicates that it was broadly contemporaneous with the initial subduction of the Chugach terrane and the onset of Late Jurassic to Early Cretaceous Gravina arc activity (Cohen and Lundberg, 1993). The southern end of the Wrangellia superterrane may have undergone crustal tension locally during the onset of widespread subduction along its western edge.

**Early to middle Cretaceous**

No significant mineral deposits of Neocomian age (144-119 Ma) have been identified in Alaska. However, middle Cretaceous time was characterized by significant gold vein-forming events in interior Alaska and by the formation of a variety of pluton-related mineral deposits in rocks of the Wrangellia superterrane, following its accretion onto southern Alaska, and in the adjacent inboard fleshy basin (Fig. 7).
The Brookian orogeny, which continued through the early Early Cretaceous in northern Alaska, included ongoing development of the Brooks Range fold and thrust belt and blueschist facies metamorphism of the subducted Arctic Alaska terrane (Moore et al., 1994). This tectonism also affected rocks that now make up the Seward Peninsula, where shallow-water and shelf facies sedimentary rock sequences of the Seward terrane were subjected to high-pressure metamorphism (Till and Dumoulin, 1994). The tectonic style controlling major structures is controversial; structures may reflect regional compression that continued into the middle Cretaceous (Till et al., 1993), regional tension between about 130 and 90 Ma (Miller and Hudson, 1991), or local extension in a broader contractional orogen (Gottschalk and Snee, in press). Middle Cretaceous extension may also have been widespread in the Ruby geanticline and the Yukon-Tanana terrane (Miller and Hudson, 1991; Pavlis et al., 1993). Granitic plutonism was coeval with the middle Cretaceous tectonism on the Seward Peninsula, in the Yukon-Tanana terrane, and in the Ruby geanticline; middle Cretaceous plutonism, however, has not been recognized in the Brooks Range. This regionally extensive thermal episode likely drove major gold vein and polymetallic vein-forming hydrothermal events in interior and northern Alaska during Albian and early Late Cretaceous.

Although a shift from compression to at least some degree of crustal extension probably characterized the Early to middle Cretaceous of much of Alaska, compressional events continued during that time across southern Alaska. In Late Jurassic and Early Cretaceous time, the Wrangellia superterrane began to approach southern Alaska, closing a series of flysch-filled basins located between the continental margin and the allochthonous block. The basinal strata are now known as the Gravina belt east of the orocline bend of southern Alaska and as part of the Katlakna terrane to the west. Albian volcanic activity along the outboard side of the basins, recording the final stages of Gravina arc magmatism (Cohen and Lundberg, 1993), led to limited deposition of volcanic and sulfide minerals in rocks of the Gravina belt in southeastern Alaska.

The oldest major gold veining identified in Alaska is in the blueschist and greenschist facies rocks of the Seward Peninsula. Anatectic gneiss, granite, and high-grade metamorphic rocks make up the core of the Seward Peninsula and have been dated at about 110 to 80 Ma (Armstrong et al., 1986). These high-temperature rocks are perhaps products of a widespread extensional episode (Miller and Hudson, 1991). Small, gold-bearing mesothermal quartz veins are common in adjacent lower grade metamorphic rocks throughout the southern Seward Peninsula. Argon thermochronology indicates that at least some of the veins formed at about 109 Ma (Ford and Snee, 1996). Cenozoic erosion of these widespread veins led to deposition of placer deposits in the Nome district, from which more than 186 t Au have been recovered.

The concentration of gold in the mesothermal quartz veins was likely a product of the Albian thermal event (Goldfarb et al., 1993). Stable isotope (Ford, 1993) and fluid inclusion data (Apodoca, 1994) support the interpretation that vein-forming fluids were derived from devolatilization of metasedimentary rocks of the Seward Peninsula. These fluids may have formed in and migrated from regions of the central Seward Peninsula that were metamorphosed beyond greenschist facies during the high-temperature event. No other major gold concentrations or areas of Cretaceous magmatism occur across the 1,200-km-long belt affected by the earlier Brookian orogeny, which further supports a genetic link between the high-temperature crustal event and gold genesis.

The Chandalar-Koyukuk district in the eastern Brooks Range is the only other location affected by Brookian orogeny that produced more than a few hundreds of thousands of grams of gold. About 11.5 t Au has been recovered from placer mines in the district (Bundtzen et al., 1994). Auriferous veins in the district fill high-angle, Albian-age fractures within greenschist facies sedimentary rocks (Dillon et al., 1987). The lode occurrences are located about 30 to 40 km north of the boundary between the Brooks Range and the Ruby geanticline. The numerous plutons of Albian age located along the northern edge of the geanticline (Patton and Box, 1989) may have been significant heat sources for driving hydrothermal fluid flow, which could explain the gold concentration in this limited area of the Brooks Range (Goldfarb et al., 1993).

Polymetallic vein and carbonate replacement occurrences scattered across the Seward Peninsula (Gamble and Till, 1993) are undated, but a spatial association with the high-grade metamorphic rocks and middle Cretaceous plutons suggests a genetic relationship to the high-temperature episode. Silver-bearing, base metal-rich veins hosted by high-grade metamorphic rocks at the Independence and Omak deposits lie within about 4 km and 13 km, respectively, of exposed plutons. Lead isotope data for sulfides from the veins are similar to data from the nearby plutons, and a magnesian iron skarn is located between veins of the Independence deposit and a 100 Ma granite (R. Newberry, written commun., 1995). No data exist, however, that would permit comparison of the chemistry of hydrothermal fluids in these polymetallic occurrences with that of the apparently more abundant gold-bearing veins.

Significant formation of gold veins in the middle Cretaceous was also coeval with high-temperature events in the Yukon-Tanana terrane. Voluminous igneous activity in the Yukon-Tanana terrane between 95 and 85 Ma (Poster et al., 1987; Newberry et al., 1997b) occurred in response to widespread crustal extension and/or to the accretion and underplating of the Wrangellia superterrane to the south (Pavlis et al., 1993). Strontium and Pb isotope data support this subduction-related origin (Newberry et al., 1991). Small, auriferous quartz veins that formed during this event were eroded in the Cenozoic to form placers that have yielded 342 t Au, about 75 percent of which comes from the Fairbanks district (Bundtzen et al., 1994). Although lode production has historically been insignificant in the Yukon-Tanana terrane, recent drilling of vein-stockwork systems near Fairbanks (the Fort Knox and Ryan Lode deposits) indicates a combined resource of 155 t Au (McCoy et al., 1997). Gold-rich tungsten skarns are common in the contact zones surrounding many of the auriferous, middle Cretaceous tonalite, granodiorite, and granite bodies (Newberry et al., 1990).

Gold-bearing quartz veins in the Yukon-Tanana terrane are hosted by Paleozoic and older (?) greenschist to amphibolite facies sedimentary rocks and by middle Cretaceous intrusive
The composition of the hydrothermal fluids is generally similar to that from other gold-bearing quartz veins in metamorphic terranes (Goldfarb et al., 1997). Both metamorphic (Goldfarb et al., 1997) and magmatic (McCoy et al., 1997) sources have been hypothesized for the ore fluids. Whatever the fluid source, geochronologic data clearly indicate some type of genetic connection between gold veining and middle Cretaceous magmatism. At both the Ryan Lode and Fort Knox deposits, Au-bearing veins dated at 79 ± 1 Ma cut porphyry intrusions dated at 91 ± 1 Ma (McCoy et al., 1994), indicating coeval magmatism and ore formation. To the southeast, in the Richardson placer gold district (Wanner, 1977), source rocks for the placers have been mainly eroded away, but Wanner (1985) noted the presence of Sn-bearing greisen in the Sihlyemenkat area that could be a source for some of the placer tin. Tin-bearing middle Cretaceous plutons of the Ruby batholith contrast with the lack of tin mineralization in middle Cretaceous plutons in the adjacent Yukon-Tanana terrane and on the Seward Peninsula, which probably reflects different sources for the middle Cretaceous granites. Plutons of the Ruby geanticline are predominantly crustal melts, and high concentrations of Sn and other lithophile elements may reflect prior enrichments in the crustal protolith (Miller, 1989).

Precious metal-rich gossans at the Illinois Creek polymetallic vein deposit also occur within sedimentary rocks of the Ruby geanticline (Gillerman et al., 1986). Both the ore and an adjacent pluton have been dated at about 113 Ma (R. Newberry, written commun., 1985), suggesting that the Illinois Creek deposit is an additional product of middle Cretaceous plutonism in the Ruby terrane.

Uranium- and REE-rich quartz veins at Mount Prindle (Burton, 1981) occur in syenite and granite of a small early Late Cretaceous alkaline complex that intrudes Cambrian rocks of the Wickersham terrane (Jones et al., 1987), a small translated fragment of the Paleozoic North American miogeoclone now located along the northern edge of the Yukon-Tanana terrane. This is the only significant occurrence of its kind in east-central Alaska. The igneous rocks are similar in composition to those of the Tombstone Suite in westernmost Yukon Territory, which have also been explored for U-bearing veins (Woodworth et al., 1991). Post-middle Cretaceous separation of the Mount Prindle ores from rocks of the Tombstone Suite along the Tintina fault system is a plausible scenario.

The Wrangellia superterrane, along with inboard flysch deposits of the Gravina and related basins, collided with the continental margin of mainland Alaska sometime in the middle Cretaceous. It may have first come in contact with the mainland in the Middle Jurassic and then moved north along a dextral strike-slip system (McClelland and Gehrels, 1992). In mainland Alaska, the Denali fault system now separates the Jurassic and Cretaceous flysch on the landward margin of the Wrangellia superterrane from the Yukon-Tanana terrane to the north. Between about 120 and 100 Ma, a suite of dominantly quartz monzonitic and dioritic plutons (the northern part of the Nutzotin-Chichagof belt of Hudson, 1979) intruded sedimentary rocks of the Gravina belt and the northern part of the Wrangellia terrane in what is now the Wrangell Mountains of eastern Alaska and the southern Alaska Range (Richter et al., 1975). It is uncertain if these plutons are part of basement to the Gravina area and therefore a consequence of outboard subduction and underplating of the Chugach terrane. The plutons are significant for hosting copper porphyry occurrences and causing the formation of adjacent auriferous skarns, both now exposed in the southeastern corner of mainland Alaska. This spatial association between copper porphyry deposits and gold skarns is common worldwide, especially in subduction and back-arc basin settings where dioritic intrusions are derived from primitive oceanic crust (Ray and Webster, 1991). This magmatism may also have been the driving force for formation of the nearby Kennecott-type copper deposits.

Richter et al. (1975) identified eight copper porphyry deposits hosted by middle Cretaceous stocks in the northern Wrangell Mountains. Cumulative known and inferred resources are roughly 1,000 Mt averaging 0.20 to 0.35 percent Cu. Sulfide minerals that occur in stockworks and as disseminations include pyrite, pyrrhotite, chalcopyrite, and molybdenite within potassically altered rocks. About 80 percent of the ore is hosted by quartz diorite-porphyry at Orange Hill and granodiorite-porphyry at Bond Creek. These two large deposits also contain about 0.02 percent Mo, and Orange Hill contains minor gold and silver enrichments. Hollister et al. (1975) reported a classic potassic-phyllic-argillic-propylitic alteration zoning pattern at both Orange Hill and Bond Creek. This model does not, however, characterize the more dioritic porphyry systems, such as the Baultoff deposit, located 65 km east of Orange Hill (Hollister, 1978). Both the phyllic and argillic zones are absent from the Baultoff deposit, and the copper ore occurs in stockworks cutting both the potassic and propylitic zones.

West of the Wrangell Mountains, emplacement of a plutonic complex into flysch of the Kahtna terrane included formation of the large Pebble Copper porphyry system. This event also may have resulted from subduction of the Chugach terrane below the Wrangellia superterrane and adjacent flysch basin. Late-stage hydrofracturing of a porphyryic granodiorite in the complex led to widespread distribution of sulfide-rich stockwork veins. Pyrite, chalcopyrite, bornite, and molybdenite are common sulfide phases, accompanied by gold that is almost always in association with pyrite (Young et al., 1996). Ore reserves associated with sulfidized igneous rock include 420 Mt of 0.35 percent Cu, 0.4 g/t Au, and 0.015 percent Mo (Young et al., 1997). Hydrothermal K feldspar from the core of the deposit has been dated at 90.5 ± 4.5 Ma by K-Ar methods (Bouley et al., 1995).

Middle Cretaceous calcic iron, copper, and gold skarns occur within Late Triassic limestones of the Wrangellia ter-
rane on both the northern (Richter et al., 1975) and southern (MacKevett, 1976) sides of the Wrangell Mountains. The most significant of these, the Nabesna copper skarn, is located about 15 km northwest of the Orange Hill porphyry deposit. Monzodiorite at the mine has been dated at 114 to 109 Ma by K-Ar methods (Richter et al., 1975). About 1.87 t Au has been recovered from pyrite lenses in fractured limestone between the igneous rocks and the garnet-pyroxene-dominant skarn (Wayland, 1943). About 200 km to the northwest, in the southern Alaska Range, the Zackley copper skarn is associated with limestone and quartz monzonite of middle Cretaceous age (Newberry et al., 1997b). Gold occurs with disseminated chalcopyrite, bornite, and pyrite in garnet-pyroxene skarn and in sulfide bodies in adjacent marble. The highest gold grades are in malachite-rich, supergene assemblages. The orebody is believed to contain 1.3 Mt grading 2.6 percent Cu and 6 g/t Au (Bundtzen et al., 1994).

The Kennecott copper deposits, about 75 km south of Orange Hill, yielded 544,000 t Cu and 280 t Ag between 1913 and 1938 (MacKevett et al., 1997). Massive, predominantly chalcopyrite ores at Kennecott are hosted by Late Triassic Chitistone Limestone, generally within 100 m of underlying tholeiitic Nikolai Greenstone. The greenstone is indicated to contain an anomalously high background of 160 ppm Cu (Armstrong and MacKevett, 1976). MacKevett et al. (1997) hypothesize that residual brines trapped in the sedimentary rocks traveled downward to leach the copper from the greenstone, transported the metal back upward, and deposited it largely as bornite in the lower parts of the Chitistone Limestone. At temperature waned, bornite was replaced by massive chalcopyrite. Steep faults extending upward from karst zones host most of the ore. These faults developed during the Late Jurassic and Early Cretaceous deformation associated with collision of the Wrangellia superterran against what is now southern Alaska, leading MacKevett et al. (1997) to suggest that the hydrothermal event was initiated by nearby middle Cretaceous magmatism. Alternatively, Silberman et al. (1978) believed that replacement of bornite by chalcopyrite did not occur until long after accretion of the superterran, most likely resulting from low-temperature convection of meteoric waters driven by late Oligocene and younger magmatic episodes. This same hydrothermal activity, whether Cretaceous or Tertiary in age, is probably responsible for widespread formation of vein and replacement deposits containing native copper and Fe- and Cu-bearing sulfide minerals within Nikolai Greenstone of what is now south-central Alaska.

Smaller, yet similar, mineral occurrences hosted by the Wrangellia terrane are found elsewhere within the northern cordillera, reflecting widespread tectonic fragmentation of the basalt-dominated terrane. Small, basaltic-hosted copper deposits occur within the Nikolai Greenstone as far north as the Susitna River, on the south side of the Alaska Range. To the south, calc-alkaline volcanics on Vancouver and Quadra Islands and in southwestern Yukon Territory also host epigenetic copper deposits (Dawson et al., 1992). Additionally, massive sulfide bodies in the Denali deposit on the south side of the Alaska Range have many features in common with the Kennecott oresbodies. Here chalcopyrite-dominant, stratiform bodies are hosted by argillaceous limestone immediately above the Triassic Nikolai Greenstone (Stevens, 1971).

Bundtzen et al. (1994) reported that the sulfide bodies at the Denali deposit contain 4.5 Mt of about 2 percent Cu. Leaching of copper from the basalts of the Wrangellia terrane was a widespread post-Late Triassic, presumably middle Cretaceous event.

Contemporaneous with middle Cretaceous magmatic hydrothermal events in mainland Alaska were the final stages of the 60- to 65-m.y.-long Gravina belt continental margin accretion of the Wrangella, Alexander, and Taku terranes and the overlapping Gravina belt flysch. The plutons generally are included in the temporally and spatially overlapping Klukwan-Duke belt of ultramafic and mafic rocks and the Admiralty-Revlaggedo belt of calc-alkaline intrusions (Brew and Morrell, 1983). Emplacement of these syn-deformational plutons at mid-crustal and deep crustal levels was probably in response to subduction of the Chugach terrane along the western side of the Wrangellia superterran (Berg et al., 1972). They were emplaced along the suture between the Gravina flysch basin, which juxtaposed rocks of the Wrangellia superterran against those of the Yukon-Tanana and Stikine terranes to the east.

The Klukwan-Duke belt of middle Cretaceous mafic-ultramafic complexes extends for more than 500 km along southeastern Alaska in a roughly 40-km-wide zone in or adjacent to rocks of the Gravina belt. The ultramafic rocks are generally distinguished, at least in part, by concentric zoning that consists of a dunite core that grades outward through peridotite to olivine pyroxenite and hornblende pyroxenite (Irvine, 1974). The Albian age and spatial association with Gravina belt basalts suggest that these rocks may be the final magma pulses of the Gravina arc, emplaced along the suture between the Wrangellia superterran and the continental margin backstop (Saleeb, 1992). Taylor and Noble (1989) suggested that the bodies formed by multiple injections of crystallizing ultramafic magmas. Irvine (1974), however, suggested that each complex formed during a single crystal-setting and fractional crystallization episode. Complexes were subsequently diapirically emplaced as mixtures of crystals and intercumulus fluid during a period marked by lateral compression and recumbent folding.

The outer hornblende pyroxenite zone of many of the ultramafic complexes consists of diopсидic augite, hornblende, and as much as 15 to 20 vol percent magnetite. Toward the core, the magnetite decreases abruptly with a corresponding increase of olivine (Taylor and Noble, 1969). Complexes at Klukwan, Snettisham, Union Bay, and Duke Island are the largest and economically most important. Klukwan alone has been estimated to contain 3.175 Mt of rock averaging 16.8 percent Fe; an adjacent alluvial fan contains 907 Mt grading 10.8 percent Fe. The deposit also contains 454 Mt of titaniferous magnetite averaging 0.08 ppm platinum-group metals (Stil, 1984). Ilmenite generally ranges between 2 and 3 percent in most of the complexes but reaches 4 to 5 percent in the more massive magnetite zones at Snettisham and Klukwan.

Podiform chromite occurs in small, serpentinized bodies of both olivine-rich and olivine-poor peridotite at Red Bluff Bay on central Baranof Island, west of the Klukwan-Duke
belt. The ultramafic rocks occur in the Chugach terrane and may represent bodies tectonically displaced from the Klukwan-Duke trend (Loney et al., 1975). The Fe-rich chromite lenses are the only significant chromite-bearing mineral occurrences known in southeastern Alaska.

Granodiorite and gabbro bodies of the Gravina magmatic arc intrude Cambrian and older strata of the Wales Group on southern Prince of Wales Island. Fe-Cu-Au skarn deposits occur where these intrusive rocks are in contact with marble of the Wales Group. The middle Cretaceous skarns are located only about 40 km southwest of similar skarn deposits of Middle Ordovician age in the Deson Formation on the Kasaan Peninsula. The most productive middle Cretaceous deposit, the Jumbo mine, yielded about 4,500 t Cu, 2.7 million g Ag, and 218,000 g Au from chalcopyrite-rich garnet-diopside skarn that averaged 4 percent Cu and 68 g/t Ag (Kennedy, 1953).

Middle Cretaceous basalts overlying flysch of the Gravina belt, a few kilometers west of Juneau, reflect the limited remains of the extrusive part of the Gravina arc (Cohen and Lundberg, 1993). Bands and disseminations of pyrite, occasionally associated with base and precious metal enrichments, are common in adjacent volcanioclastic sedimentary rocks. Minor occurrences on Douglas Island, such as Alaska-Treasure, Jersey, and Yakima, are likely products of such volcanogenic activity.

Latest Cretaceous

By latest Cretaceous time (84-66 Ma), northern Alaska was tectonically stable, whereas magmatic-arc development began in the southern half of the state during accretion and northward subduction of the Kula plate. The Kula plate split from the Farallon plate sometime in middle Cretaceous within the Pacific basin. Deep sea fans eroded from emergent source areas in southeastern Alaska and British Columbia, and subordinate ocean-floor basalts were carried northward on the Kula plate. They formed an accretionary complex now known as the Valdez Group of the Chugach terrane that reached the south-central Alaska continental margin by the latest Cretaceous (Pflaeker et al., 1994). As a consequence of Kula plate subduction, plutonic and lesser volcanic-arc rocks that crop out in the Alaska Range and Talkeetna Mountains were starting to develop by the beginning of Maastrichtian time in the Peninsular terrane, in the flysch belt north of the Wrangellia superterrane, and in a series of small terranes along the Denali fault system (Moll-Staloup, 1994). The resulting subduction-related arc, active through Eocene time, is at least 150 km wide and extends along a northeasterly trend from the northwestern Alaska Peninsula near Mount McKinley. Coeval magmatism, perhaps part of a single widespread event (Moll-Staloup, 1994), was also common throughout the Cretaceous Kuskokwim basin, west of the Alaska Range-Talkeetna Mountains magmatic belt.

Tin occurrences are associated with Campanian and Maastrichtian anorogenic magmatic activity in northern Alaska (Fig. 8). Cold-bearing, generally poly metallic veins and breccias appear to be genetically related to plutonism in the Kuskokwim basin and parts of the Alaska Range. Copper-rich volcanogenic massive sulfide deposits originated during submarine volcanism offshore on the Kula plate and are now exposed in the Prince William Sound area.

Tin granites were emplaced in both metamorphosed and relatively unmetamorphosed sedimentary rocks at 80 to 70 Ma in the northwestern Seward Peninsula. It is uncertain whether these highly evolved granites and syenogranites represent magmas residual to the more mafic, middle Cretaceous bodies that formed 100 km to the southeast and are temporally associated with mesothermal gold vein formation. Hudson and Arth (1983) indicated that the relatively shallow emplacement of these anorogenic bodies was a final stage of 40 m.y. of continuous magmatism on the Seward Peninsula. Alternatively, Newberry et al. (1997b) suggested from trace element geochemistry that latest Cretaceous tin granites are products of crustal extension, whereas middle Cretaceous plutonism is subduction related.

Seven tin granites are exposed and two are inferred at depth in the Seward Peninsula (Hudson and Arth, 1983). These tin granites probably correlate with a similar group

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**Figure 8.** Latest Cretaceous time in Alaska was marked by anorogenic magmatism yielding tin- and uranium-rich rocks in the north; by magmatic-arc activity in southwestern Alaska that drove pluton-related gold-vein and mercury-rich epithermal-vein formation; and by sea-floor volcanism south of the continental margin that led to development of copper-rich volcanogenic massive sulfide bodies. Inferred terrane configuration from Plafker and Berg (1994). See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.
exposed in eastern Siberia (Swanson et al., 1990). On the peninsula, cassiterite is generally in greisenized plutonic cupolas, and in adjacent marbles it is found as pyroxene-garnet-tourmaline-anorthite-cassiterite skarn (Swanson et al., 1990). Uranium and REE enrichments are commonly associated with many of these evolved plutons. The tin resource in northwestern Alaska is a function of the degree of erosion (Swanson et al., 1990); significant lode reserves remain where there is little or no erosion, and significant placer deposits are more common where the plutons have been partly eroded. In areas of deeply eroded plutons, little of economic value occurs in lodes or placers. About 2,700 t Sn has been recovered from lodes and placers of the Seward Peninsula, representing more than 90 percent of Alaska's historic production. Lode reserves at the Lost River deposit include 22.3 Mt of 0.15 percent Sn, 16.3 percent fluorite, and 0.03 percent WO3 (Bundtzen et al., 1994). In addition, beryllium-fluorite-rich veins that replaced limestone at the Lost River deposit contain 4,500 t Be and represent one of the world's largest beryllium reserves (Stainsbury, 1988).

Calc-alkaline plutons ranging from tonalite through granite were shallowly emplaced between about 89 and 78 Ma in the eastern Yukon-Koyukuk basin. Isotopic and trace element geochemical data (Miller, 1989) suggest that igneous rocks have no continental crust component and were probably derived from oceanic mantle or volcanic crustal material. Uranium-bearing minerals in quartz veiins and felsic dikes cut igneous rocks dated at 84 to 80 Ma in this plutonic belt (Miller, 1976).

The initiation at 75 Ma of a magmatic event lasting 20 m.y. along a northeast-trending belt 300 km long and 200 km wide across southwestern Alaska (Moll-Stalcup, 1994) led to the widespread formation of pluton-related, gold-bearing quartz veins and epithermal cinnabar- and/or stibnite-bearing veins during the Maastrichtian (Bundtzen and Miller, 1997; Gray et al., 1997). Following the Late Jurassic and Early Cretaceous collision of the Togiak and Yukon-Koyukuk arcs against the western edge of Alaska, the 70,000-km2 Kuskokwin basin overlapped and incorporated numerous small terranes in what is now southwestern Alaska. Marine turbidites filled the basin between Albian and Turonian time (Decker et al., 1994). Calc-alkaline dikes, stocks, and volcano-plutonic complexes consisting of mainly quartz monzonite were shallowly emplaced in the basin and in adjacent terranes soon after cessation of sedimentation. Isotopic and trace element geochemical data for the igneous rocks are characteristic of subduction-related are magmas generated in a mantle wedge. This suggests that plutons of the Kuskokwin basin, Alaska Range, and Talkeetna Mountains formed an anomalously wide arc in response to the northerly directed subduction along south-central Alaska (Moll-Stalcup, 1994).

Gold placer deposits are widespread in southwestern Alaska and show a strong spatial association with igneous rocks. The Iditarod district has yielded 48.5 t of placer gold (Bundtzen et al., 1984) and is Alaska's third most productive placer camp. Many productive placers in the Kuskokwin basin have been traced to upstream, economically less significant lode systems hosted by igneous rocks. Auriferous, quartz-tourmaline veins, such as those at the Golden Horn deposit, often contain abundant scheelite and base metal sulfides.

Where plutons intrude Ordovician carbonate rocks of the Farewell terrane, a fragment of the ancestral continental margin now located adjacent to the Kuskokwin basin, copper- and gold-rich calcic skarns formed. The most significant of these, the Nixon Fork deposit, produced 1.87 t Au and contains a resource of almost 11 t Au (Bundtzen et al., 1994). Potassium-argon ages for mineralized plutons at the Nixon Fork, Golden Horn, Vineale Mountain, and Beaver Mountains occurrences, believed to approximate the time of metallic mineralization, range between 70 and 65 Ma (Szymigala, 1993). One Ar/Arg date of 67 Ma for hydrothermal muscovite at the Fortyseven Creek occurrence (John Gray, pers. commun., 1992) confirms a Maastrichtian age for gold ore deposition. Similar Pb isotope compositions for many of the plutons and sulfide minerals in the mineral deposits in southwestern Alaska favor a regional magmatic lead source (Szymigala, 1993).

Epithermal cinnabar and/or stibnite vein systems are also scattered throughout southwestern Alaska. They include the Red Devil mine, which produced 35,000 tles of mercury and was Alaska's only significant mercury producer. Stable isotope data from the epithermal occurrences indicate that fluids and sulfur were primarily derived from sedimentary rocks of the Kuskokwin basin, perhaps during localized devolatilization associated with emplacement of igneous bodies (Goldfarb et al., 1990). A Ar/Arg date of between 73 and 72 Ma from a number of the lodes indicates that hydrothermal activity was coeval with the onset of Late Cretaceous magmatism in the Kuskokwin basin (Gray et al., 1992). Zoning at the Red Devil mine, from shallow cinnabar-rich to deeper stibnite-rich ore, as well as anomalous gold values in many of the epithermal veins (Gray et al., 1997) suggests that these shallowly emplaced ore systems could be the upper reaches of deeper mesothermal Au-bearing vein systems. Near the Iditarod district, recent exploration beneath a small stibnite occurrence at Donlin Creek has led to the discovery of more than 110 t Au in arsenopyrite-bearing quartz stockworks cutting granitic porphyry dikes and sills.

Paleozoic and Precambrian(?)-schist in the Kantishna Hills in the westernmost part of the Yukon-Tanana terrane, located north of the Alaska Range in the center of the state, is cut by auriferous, stibnite-rich quartz veins. Approximately 2,300 t Sb and significant silver and gold have been produced from the lodes and related placers. The genesis and age of deposits within Alaska's only significant antimony district are uncertain. Bundtzen (1988) suggested that the metals may have been leached from surrounding metamorphic rocks, but the driving force for the hydrothermal event is not known. Some workers suggest a genetic relationship between the metalliferous veins and quartz porphyry to gabroic dikes that have a hornblende K-Ar age of 81.3 Ma (Bundtzen and Turner, 1978).

The Alaska Range-Talkeetna Mountains magmatic arc is formed landward of the Wrangellia superrterane and south and east of the Kuskokwin basin between 74 and 55 Ma (Reed et al., 1983). It includes one group of plutons dated at between 69 and 64 Ma (Reed and Nelson, 1977; Swainbank et al., 1977) that trends northeast-southwest for about 200 km along the southwestern side of the Alaska Range. These plutons of varied composition intrude an exotic and poorly
understood small terrane of Devonian through Jurassic sedimentary and volcanic rocks (the Chulitna terrane of Jones et al., 1982) and Jurassic to Cretaceous flysch. Gold-bearing, polymetallic pipes and veins of the Chulitna district (Hawley and Clark, 1974) and Au-bearing veins in the Mount Estelle area (Crove et al., 1990) cut intrusive rocks and may be magmatic in origin. Alteration at one of the larger polymetallic lodes, developed by the Golden Zone mine, has been dated at 68 Ma (Swainbank et al., 1977), a date identical to that of the host quartz monzodiorite.

Initiation of sea-floor volcanism, perhaps associated with spreading along the Kula ridge near the triple junction of the Kula, Farallon, and the North America plates, led to a 15- to 30-m.y.-long period of Fe-Cu-Zn-rich volcanogenic massive sulfide formation. The resulting Cyprus- and Besshi-type deposits are now exposed within and near ophiolitic sequences throughout Prince William Sound and the eastern Chugach Mountains. The older mineral occurrences of this episode that formed within the late Campanian to early Maastrichtian sedimentary rocks of the Valdez Group are recognized as part of the Chugach terrane, which was accreted to south-central Alaska in latest Cretaceous or early Tertiary time (Plafker et al., 1984). The Milda mine is the most significant pyrrhotite-chalcopyrite-sphalerite deposit associated with Late Cretaceous tholeiitic basalt of the Valdez Group; it produced more than 1,360 tons Cu with grades of 3.4 percent Cu and 1.5 g/t Au (Crove et al., 1992).

**Paleocene and early Eocene**

No significant lodes deposits were formed in the northern half of Alaska during the Cenozoic, with the exception of a large sedimentary rock-hosted uranium deposit on the Seward Peninsula (the Death Valley deposit) and some minor Cu-Mo porphyry and tin greisen-skarn occurrences in the Yukon-Tanana terrane. Earlier formed lodes were eroded during this time, especially in the Yukon-Tanana terrane and the Seward Peninsula, becoming significant gold placers that have been responsible for much of the state's past production. Lode formation was widespread, however, in the tectonically active southern part of Alaska (Fig. 9). Paleocene base metal-rich skarns and early Eocene tin greisens developed in association with arc magmatism in the western Alaska Range. Mesothermal, Au-bearing quartz veins developed throughout the fore-arc region of south-central and southeastern Alaska. Distal to the continental margin, Fe-Cu-Zn volcanogenic massive sulfide deposits continued to form during hydrothermal activity within the Kula plate in the north Pacific basin.

The largest uranium resource in Alaska, the Death Valley sandstone-type uranium deposit, was discovered in 1977 in the southeastern part of the Seward Peninsula. It contains at least 450 tons U_3O_8 (Dickinson et al., 1987). Oxygenated ground water leached uranium from the middle Cretaceous Darby pluton, recognized by Miller and Bunker (1976) as highly enriched in uranium and thorium. Meta-autunite and lesser coffinite were deposited in more reducing, early Eocene clastic-rock environments that contained abundant carbonized wood and minor coal (Dickinson et al., 1987). This is the only significant sedimentary rock-hosted uranium deposit recognized in Alaska.

Small and isolated hypabyssal porphyritic stocks were emplaced during the Paleocene, and probably slightly earlier, into sedimentary rocks of the Chulitna-Tanana terrane north of the Alaska Range and within about 25 km of the Canadian border. Chalcopyrite and molybdenite in stockworks and disseminations occur in highly altered granite-porphry, granodiorite, and quartz latite-porphry. All recognized porphyry systems are associated with subvolcanic intrusions, are surrounded by large alteration halos, have a pyrrhotite-chalcopyrite-molybdenite sulfide assemblage, and have some supergene enrichment (Foster et al., 1987). The largest known resource is the Taurus deposit, which contains 408 Mt of 0.5 percent Cu and 0.07 percent Mo (Chipp, 1988). Three of the porphyritic bodies have been dated between 64 and 56 Ma, whereas similar occurrences in adjacent Yukon Territory...
range in age between 71 and 68 Ma (Sinclair, 1986). The cause of magmatism is uncertain but the back-arc position of the Alaskan occurrences and the older ages to the east do not fit a simple subduction model.

Tin-bearing greisens, veins, skarns, and placers are associated with these hypabyssal plutons dated at 60 to 50 Ma in the Circle district and Lime Peak area of the Yukon-Tanana terrane, but they have not been widely developed. These peraluminous granite plutons are associated with basaltic dikes and have trace element signatures indicative of formation in a within-plate, extensional setting (Newberry et al., 1997b). Cassiterite occurs most commonly with garnet, pyroxene, chlorite, pyrrhotite, and fluorite in the skarn occurrences and with zinnwaldite, topaz, chlorite, tourmaline, and base metal sulfide minerals in the greisens. A tungsten-rich molybdenum porphyry dated at 56 Ma at Bear Mountain along the southeastern flank of the Brooks Range (Barker and Swainbank, 1996) could be representative of the same extensional event.

Paleocene plutons within the Alaska Range-Talkeetna Mountains magmatic arc dated at 75 to 50 Ma are associated with Cu- and Pb-Zn-bearing skarns where they are in contact with carbonate beds of the Peninsular and Farewell terranes. Pb-Zn-Ag, and Cu-rich skarns of the Farewell district (Szumigala, 1985) are hosted by Cambrian to Middle Devonian marbles of the Farewell terrane that was faulted westward from the Paleozoic continental margin. Although the most significant of these skarns are associated with Oligocene granodiorite dikes in the Tin Creek area (Szumigala, 1986), some mineralization is associated with a quartz porphyry dated at 61.6 Ma (Bundtzen et al., 1988). More than 9 Mt of greater than 1 percent Cu (Bundtzen et al., 1994) is contained in the Kasna Creek deposit in rocks of the Peninsular terrane. The skarn deposit, comprising hematite and lesser magnetite and chalcopyrite in Late Triassic carbonate rocks, is spatially associated with a quartz monzonite pluton dated at 61 Ma (Nelson et al., 1983). At Crevice Creek, Cu-bearing epidote-garnet bodies containing significant precious metal values are also hosted by Late Triassic carbonate rocks of the Peninsular terrane (Richer and Herreid, 1965). In addition, scattered polymetallic vein occurrences are associated with many of the Paleocene plutons. Among the most significant of these are the Ag- and Au-rich veins in the Bonanza Hills that cut contact-metamorphosed dacite, sandstone, and intrusive bodies within the Kahiltna terrane and are adjacent to a 64 Ma quartz monzonodiorite (Nelson et al., 1983).

Tin-bearing mineral occurrences are associated with some of the younger, peraluminous plutons of the Alaska Range area. These peraluminous plutons are in the same belt as the slightly older, polymetallic and gold lode-bearing Maastrichtian intrusions found in the Chulitna district and Mount Estelle region, respectively. Cassiterite, as well as gold, is abundant in lodes and placers of the Yentna district in the area between the Chulitna and Mount Estelle locations. Granites in the Yentna district were emplaced in Jurassic to Early Cretaceous flysch north of the Wrangellia superterrace between 56 and 52 Ma (Reed et al., 1978). Tin-bearing greisens and vein systems, including the Coal Creek deposit that contains 4.5 Mt of 0.28 percent Sn (Bundtzen et al., 1994), occur northeast of the Yentna district in undated, but probably Eocene, intrusions of the Chulitna district. Eocene metalliferous granite rocks of the southwestern Alaska Range have been correlated with terrane accretion to the south and are believed to reflect assimilation of sedimentary rocks by a mantle-derived magma (Lanphere and Reed, 1985). Tin- and W-rich greisens of about 57 Ma within the Sletit Mountain granite stock, which intrudes flysch of the Kuskokwim basin west of the Alaska Range, may be part of the same magmatic episode. Inferred resources of 58,000 to 96,000 t Sn in 26 Mt of rock (Burleigh, 1991) represent Alaska’s largest tin reserve.

The Paleocene and early Eocene interval in the southern Alaskan fore arc marks a period of voluminous and widespread mesothermal gold vein formation lasting 15 m.y. Gold-bearing veins were deposited in the Willow Creek district, the Valdez Creek district, throughout the Chugach and Kenai Mountains in south-central Alaska, and in the Juneau gold belt and Chichagof district in southeastern Alaska. The veins are hosted dominantly in greisen facies units of a number of different terranes; fluids were likely derived from metamorphic devolatilization reactions in the fore arc (Goldfarb et al., 1993). The greisen to amphibolite transition may have been significant for fluid release and gold transport. A distinct spatial and temporal association exists in the fore arc between gold veining and igneous activity. In addition, inboard-arc magmatism, which formed many of the plutonic bodies of the Alaska Range and Coast batholith, was coeval with the fore-arc events. All of these processes may be part of an extensive early Tertiary thermal event in southern Alaska driven by plate reorganizations in the north Pacific basin (Goldfarb et al., 1997).

The Juneau gold belt in southeastern Alaska has been the state’s largest lode gold producer, yielding about 211.5 t Au, mostly from the Alaska-Juneau and Treadwell mines, which still contain significant reserves. Gold-bearing veins were preferentially emplaced into competent Cretaceous igneous rocks within the sedimentary and volcanic rock sequences of the Gravina belt, Taku terrane, and Wrangellia terrane (Goldfarb et al., 1993). A shift from orthogonal to oblique plate convergence and resulting strike-slip motion is hypothesized as having led to increased permeability and widespread fluid migration at 56 to 53 Ma (Goldfarb et al., 1991; Miller et al., 1994). The genetic relationship of the ores of the Juneau gold belt to the coeval Coast batholith, 10 to 20 km to the east, is uncertain; a regional contact-metamorphic event associated with the magmatic thermal aureole cannot be ruled out as the driving force for hydrothermal activity.

Alaska’s second largest lode gold producer, the Chichagof district, which had about 25 t of past production, is located 100 km seaward of the Juneau gold belt. Auriferous quartz veins at the Chichagof and Hirst-Chichagof mines cut Cretaceous metasedimentary rocks of the Chugach terrane, and those at the Apex and El Nido mines are hosted by Jurassic diorite of the Tonsina-Chichagof belt in the Wrangellia terrane. Plutons, largely of granodiorite, intrude the Chugach terrane within about 10 km of the Chichagof and Hirst-Chichagof mines and have been dated at 52 to 51 Ma (Taylor et al., 1994). In addition, hydrothermal micas from the Apex and El Nido deposits have 40Ar/39Ar ages of 52 to 51.5 Ma (Taylor et al., 1994). The Kula-Farallon spreading ridge may
have been progressively subducted beneath the Chugach terrane from west to east in the early Tertiary (Bradley et al., 1993). This migration of the subducting spreading center and its associated slab window may explain the progressively younger ages of gold veins in the outer part of the fore arc from about 57 Ma in south-central Alaska (see Chugach and Kenai Mountains, below) to about 50 Ma in southeastern Alaska.

The Willow Creek district is the most significant lode gold system in south-central Alaska. About 19 tAu were recovered from mesothermal veins cutting a 70 to 72 Ma quartz monzodiorite to tonalite pluton of the Talkeetna Mountains batholith that intrudes rocks of the Peninsular terrane (Winkler, 1992). K-Ar dates on hornblende and muscovite from adamellite and a pegmatite indicate intrusive activity as young as about 65 Ma in the district. Hydrothermal muscovite from the Independence mine, the main gold producer in the Willow Creek district in the past, has been dated by 40Ar39Ar at 66 Ma (S. Harlen, oral commun., 1994). To the south of Willow Creek, small gold-bearing veins that formed between about 57 and 53 Ma (Goldfarb et al., 1993) are widespread in the Chugach and Kenai Mountains within greenschist facies rocks of the Chugach terrane. They are commonly spatially associated with calc-alkaline igneous rocks of the same age. Small gold-bearing veins in the Valdez Creek district are widespread in greenschist facies rocks of the MacLaren Glacier metamorphic belt (Smith, 1981), part of the Late Jurassic to Early Cretaceous flysch belt north of the Wrangellia superterrane. For the past ten years, placer deposits downstream from the veins and along Valdez Creek have been Alaska's most productive gold mine. The source lodes for Valdez Creek placers have been dated at 62 to 57 Ma (Adams et al., 1992), about the same age as granodiorite intrusions that crop out a few kilometers east of the district (Smith et al., 1988).

Sea-floor volcanism south of mainland Alaska continued into the Paleogene. Basalt and graywacke of the Paleocene and Eocene Oreo Group host lenses of massive pyrrhotite-chalcopyrite-sphalerite that record ongoing Kula plate ridge volcanism. The volcanic rocks and associated orebodies were obducted onto the south-central Alaska continental margin as part of the Prince William terrane by 51 ± 3 Ma (Pfaffker et al., 1994). One of the ophiolite sequences associated with the magmatism has been dated at 57 Ma (Crowe et al., 1992) and may be coeval with some of the metaliferous hydrothermal activity. The largest of these volcanogenic massive sulfide deposits and the second largest copper producer in Alaska, the Beatson mine, produced about 5.5 Mt of ore grading 1.65 percent Cu and 7.8 g/t of both gold and silver (Crowe et al., 1992).

Middle Eocene to the present

Strike-slip tectonics have predominated throughout southeastern Alaska since the middle Eocene. During this transcurrent regime, relatively local magmatism of uncertain cause led to a series of ore-forming events. These included middle Eocene formation of gabbroic Ni-Cu occurrences in the northwest, Cu-Mo porphyry, skarn, and polymetallic vein occurrences in the north-central, and a world-class porphyry molybdenum deposit in the southeast part of southeastern Alaska (Fig. 10; Ashleman et al., 1997; Foley et al., 1997; Newberry et al., 1997b; Young et al., 1997). On the opposite side of the north Pacific basin, convergence between the North America and Pacific plates resulted in formation of the volcano-plutonic island-arc complex of the Alaska Peninsula and Aleutian Islands. Plutonic activity associated with arc development was concentrated in two periods, the middle Eocene through the early Miocene (Meshik arc) and the late Miocene through the present (Aleutian arc; Wilson, 1985). Copper and/or molybdenum porphyry occurrences (Young et al., 1997), as well as gold-bearing epithermal vein deposits (Gray et al., 1997), are products of magmatic-driven hydrothermal activity.

A group of Tertiary layered gabbroic bodies occurs in the Chugach terrane in the Fairweather Range and on Yakobi Island in the northern part of southeastern Alaska (Foley et al., 1997). Many of these bodies are within composite plutons dominated by tonalite. They might represent feeder zones to continental margin volcanism that have probably been displaced by strike-slip motion (Pfaffker et al., 1994). Himmelberg et al. (1987) indicated K-Ar dates on biotite and hornblende of 43 to 40 Ma for the associated tonalite on Baranof Island, and Hudson and Pfaffker (1981) suggested a similar age for the eruption of the Crillon-La Pouse gabbro in the Fairweather Range. A 40Ar39Ar date of 30 Ma for biotite from a pegmatite dike cutting the Crillon-La Pouse body might be indicative of a slightly younger age for some of the magmatism.

Copper- and Ni-rich sulfide deposits occur in these gabbroic and associated noritic bodies. Pyrrhotite, pentlandite, chalcopyrite, and minor cobaltite in lenticular masses, veinlets, and disseminations near the base of the mafic plutons probably formed by separation and gravity settling of immiscible sulfide-rich phases. The Brady Glacier deposit on the eastern edge of the Crillon-La Pouse pluton is one of the largest nickel resources in the United States, containing 91 Mt of 0.5 percent Ni, 0.3 percent Cu, and about 0.03 percent Co (Budnitz et al., 1994). The more massive ore also contains about 1.30 ppm platinum-group metals (Brew et al., 1978).

A group of calc-alkaline plutons intrudes volcanic and sedimentary rocks of the Alexander terrane east of the belt of gabbroic bodies. Granites, dated by K-Ar methods at between 42 and 31 Ma (Brew, 1988), are spatially associated with numerous Cu- and Mo-rich porphyry, skarn, and polymetallic vein occurrences in the Glacier Bay region. The Margerie Glacier occurrence, probably the most significant copper porphyry system recognized in southeastern Alaska, contains 145 Mt of 0.2 percent Cu and significant amounts of silver, gold, and tungsten in a porphyritic quartz monzodiorite stock (Brew et al., 1978). The Nunatak skarn occurrence, primarily chalcopyrite- and molybdenite-bearing stockworks adjacent to a quartz monzinite-porphry stock, contains about 117 Mt of 0.04 to 0.06 percent Mo and 0.02 percent Cu (Brew et al., 1978). Copper-rich skarns at the Rendu Glacier and Alaska Chief occurrences are associated with quartz diorite bodies. The cause for the relatively localized, metaliferous magmatic event is uncertain. Brew (1988) hinted that the granites may be remnants of a siliceous expression to the gabbroic systems located a few tens of kilometers to the west.
Several late Oligocene granite and gabbro stocks intrude the Coast batholith and adjacent high-grade metamorphic rocks of the Yukon-Tanana terrane in the southern part of southeastern Alaska. The Quartz Hill igneous complex, which hosts a world-class porphyry molybdenum deposit, consists of porphyritic quartz monzonite and quartz latite that was shallowly emplaced between about 30 and 27 Ma (Hudson et al., 1979). Molybdenite occurs in quartz veins and as fracture coatings within the intrusive rocks and constitutes a resource possibly as large as 1,360 Mt grading 0.136 percent Mo (Bundtzen et al., 1994). Isotopic data suggest that the magmas at Quartz Hill and at the Burroughs Bay molybdenum occurrence, 85 km to the north, formed as simple melts of the lower crust or mantle and were unrelated to older calc-alkaline, subduction-related magmas; they were emplaced during regional extension, perhaps in association with bimodal magmatism (Hudson et al., 1981).

As first suggested by Hudson et al. (1979, 1981), classification of the Quartz Hill deposit is difficult. Although the Quartz Hill igneous complex is believed to have formed in an extensional environment, it lacks the intense silicification, multiple ore shells, and fluorine enrichment described by
White et al. (1981) as representative of Climax-type systems. The fluid inclusion chemistry (Theodore and Menzie, 1984) is more like that of the calc-alkaline, subduction-related porphyry deposits of British Columbia than of Climax-type orebodies. However, the granitic host rocks, the presence of topaz, the low $^{87}$Sr/$^{86}$Sr values, possible bimodal volcanism, and the relatively young age of the Quartz Hill deposit are inconsistent with a subduction-related origin (Hudson et al., 1981), as is the transform nature of the continental margin at this time.

Late Tertiary extension in southeastern Alaska is also recorded 150 km north of the Quartz Hill deposit by tin greisens and tin and Zn-Pb skarns at Groundhog basin and Glacier basin. These occurrences are associated with an altered early Miocene granite stock. Newberry and Brew (1988) hypothesize that a low magmatic oxidation state favored generation of the Sn-rich ore systems relative to the more oxidized nature of the magmas which formed the Mo-rich ore at Quartz Hill.

Copper porphyry and/or molybdenum occurrences are associated with magmatism of both the Mesihik and Aleutian arcs along the entire length of the Alaska Peninsula and Aleutian Islands of southwestern Alaska. Subduction-related hypabyssal bodies of andesite, dacite, quartz diorite, and tonalite intrude Late Jurassic to Holocene sedimentary rocks, and many of these bodies show evidence of subsequent hydrothermal alteration. Most of the porphyry occurrences contain 0.3 to 0.5 percent Cu and carry significant amounts of molybdenite (Wilson and Cox, 1983). Generally, the ore zones lack strongly anomalous gold, in contrast to the Mesozoic systems, such as Pebble Copper and those that are associated with the Jurassic Talkeetna arc. Geologic and geochemical data from the porphyries indicate characteristics common to both island-arc and continental margin porphyry systems (Wilson and Cox, 1983).

The Pyramid deposit near the southern end of the Alaska Peninsula is economically the most significant of these porphyry deposits. A 90-m-thick supergene-enriched chalcoite blanket in a quartz diorite stock with a date of 7 to 6 Ma contains 113 Mt of resources averaging 0.403 percent Cu and 0.025 percent Mo and gold values never exceeding 100 ppb (Wilson et al., 1995). Alteration at the Pyramid deposit zones outward from a biotite-rich core to the ore-bearing and pyrite-rich quartz-sericite-andalusite zone to an outer chlorite zone. Many of the other porphyry occurrences are also characterized by multiple intrusive phases and classic potassic, sericitic, propylitic, and local argillic alteration zones (Wilson and Cox, 1983). The Mike prospect of 3.65 Ma is the most significant recognized molybdenum porphyry, containing 23 Mt of 0.2 percent Mo (Church et al., 1989). Most of the dated mineral deposits on the central Alaska Peninsula, described by Wilson and Cox (1983), are Miocene or younger, but hydrothermal activity at the Rex copper porphyry occurrence, containing 0.7 g/t Au (Church et al., 1989), has been dated at 30 to 34 Ma. This suggests that more gold-rich hydrothermal systems may be associated with the older Mesihik arc.

Potential epithermal and related hot spring gold occurrences are favorable exploration targets within shallow crustal rocks adjacent to the porphyry centers (Gray et al., 1997). The Alaska-Apollo, Shumagin, and associated vein deposits of the Shumagin Islands along the southern side of the Alaska Peninsula are the only group of epithermal systems that have had significant development. The 4 t of Au recovered from 5 g/t ore at the Alaska-Apollo mine represents the only significant gold production from volcanic rock-hosted epithermal vein systems in Alaska. The vein systems of the Shumagin Islands have been classified as adularia-sericite-type orebodies (Wilson et al., 1995). These fault-controlled breccias and veins are enriched in Ag, Au, Te, Cu, Pb, and Zn. Strong argillization of volcanic host rocks extends for more than 45 m from ore shoots, and quartz-sericite-pyrite zones are common immediately adjacent to the ore (Wilson et al., 1985). K-Ar dates on hydrothermal alteration suggest that hydrothermal activity occurred between 34 and 32 Ma (Wilson et al., 1994), but it is likely that much younger epithermal and hot spring deposits exist elsewhere on the Alaska Peninsula.

Summary

The metallogenic evolution of Alaska is characterized by episodic ore formation in oceanic environments between about 600 and 150 Ma (Fig. 11). On the continental shelf, adjacent to the North American continent, Devonian through Carboniferous development of sedimentary basins that was probably intimately associated with rifting led to widespread base metal mineralization. Shale-hosted Zn-Pb-Ag, carbonate-hosted copper, and/or polymetallic volcanogenic massive sulfide deposits formed within rocks that were rotated and accreted as part of the Arctic Alaska, Yukon-Tanana, and Farewell terranes. Distal to the continent, magmatic events related to pre-Devonian oceanic-arc activity, Triassic rifting, and Jurassic oceanic-arc activity are correlated with formation of polymorphic chromite deposits, additional polymetallic volcanogenic massive sulfide systems, and Fe-Ti-Pt-enriched zoned ultramafic bodies. These ore systems were added to North America from the Middle Jurassic through middle Cretaceous by accretion of the Wrangellia superterrane and smaller terranes now exposed in southwestern Alaska and by the obduction of the Angayucham terrane over much of northern Alaska.

Orogenic deformation began in interior and northern Alaska in the Early and Middle to Late Jurassic, respectively. Obduction of oceanic crust onto the Yukon–Tanana terrane and Arctic Alaska–Seward terranes was accompanied by low-temperature blueschist facies metamorphism (Dusel-Bacon, 1991). The lack of Jurassic igneous bodies in these terranes suggests a low thermal gradient associated with the collisional events. Such conditions were not conducive to development of hydrothermal systems; metallogenic events were restricted to emplacement of previously formed mineral deposits contained in the obducted oceanic rocks.

The last 150 m.y. have been distinguished by terrane accretion and by an extensive subduction-related metallogenic epoch throughout much of the Alaska cordillera (Fig. 11). A few metaliferous systems that formed in oceanic rocks seaward of the continental margin were also accreted to Alaska at this time (i.e., the Besshi- and Cyprus-type volcanogenic massive sulfide deposits in the Chugach and Prince William terranes), but most mineral deposits developed in previously accreted rocks. The fore-arc and magmatic-arc regions of the present-day southern half of the state were especially favorable envi-
environments for ore formation. Ore genesis was driven by subduction of the Farallon plate prior to about 85 Ma, Kula plate subduction through the middle Eocene, and Pacific plate motion in association with formation of the Aleutian trench during the last 43 m.y. Copper porphyry and related skarn deposits formed during pulses of calc-alkaline arc magmatism in the overriding backstop, which was composed of the Wrangelia, Peninsular, Alexander, and Farewell terranes and the Gravina flysch belt. These magmatic systems are likely to have initiated fluid circulation that led to formation of middle Cretaceous(?), Kennecott-type copper deposit in southeastern mainland Alaska, Maastrichtian epithermal cinnabar vein systems in southwestern Alaska, and Tertiary epithermal precious metal systems of the Alaska Peninsula. Magmas that generated middle Cretaceous, Fe-rich, Alaska-type zoned ultramafic bodies of southeastern Alaska are also products of subduction.

Lode gold formation, aside from epithermal systems of the Alaska Peninsula, was concentrated in three distinct temporal and spatial events. At least the younger two, and perhaps the older event, were driven by subduction-related tectonics. In south-central and southeastern Alaska, early Eocene subduction of the Kula-Farallon spreading center led to widespread gold vein development in the Chugach terrane. At the same time, high thermal gradients resulted in gold vein formation farther landward in the fore arc, associated with more typical convergent margin processes of crustal thickening and asthenospheric upwelling. In southwestern Alaska, Maastrichtian gold veins closely associated with rocks of the Kuskokwim Mountains volcano-plutonic belt developed above the underthrust Kula slab. The tectonic regime that ultimately led to middle Cretaceous veining in the Seward and Yukon-Tanana terranes is much less certain. Early Late Cretaceous granites and gold veins in the Fairbanks district could be related to Farallon slab subduction during the accretion of the Wrangelia superterrane. Similarly, Albian veins of the Nome district could somehow be related to the northeasterly directed compression between the Farallon and North America plates and to some type of short-lived subduction zone. A great deal of controversy still exists, however, concerning the significance of possible extension within northern and interior Alaska during middle Cretaceous time.

Postcollisional, clearly anorogenic ore systems are limited in the Alaska cordillera. Many of the latest Cretaceous and Tertiary tin deposits of Alaska may be products of postorogenic crustal thinning, but their spatial overlap with slightly older metaluminous igneous rocks cannot rule out an ultimate association with subduction-related magmatism. The Quartz Hill molybdenum porphyry deposit in southeastern Alaska is the only significant postaccretionary magmatic ore system in Alaska. Most recently, the extensive network of placer gold systems in interior Alaska, platinum-bearing placers of the Goodnews Bay area, and sandstone-hosted uranium resources in Death Valley reflect Cenozoic erosion of Mesozoic mineral enrichments.

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