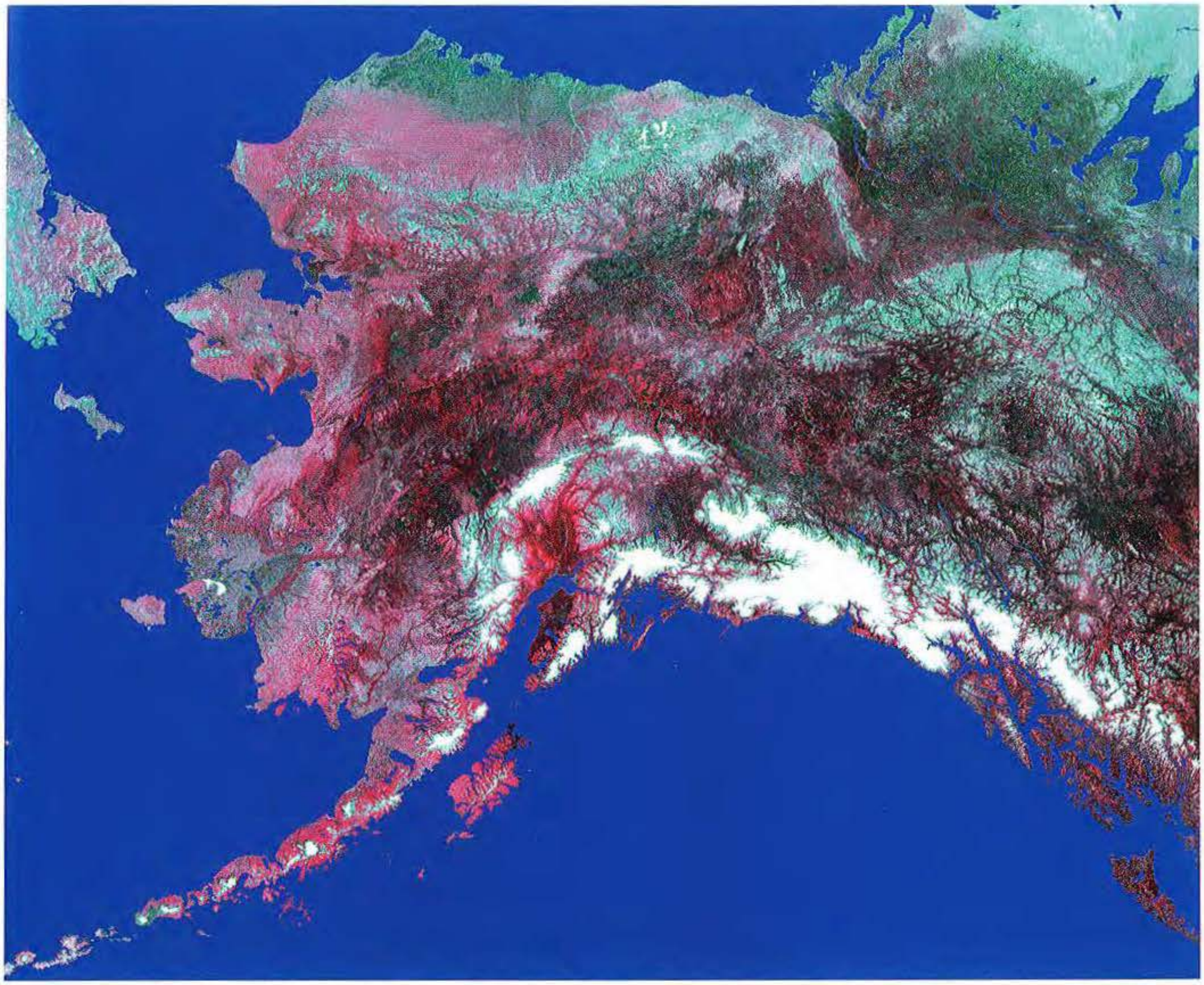
ECONOMIC GEOLOGY MONOGRAPH 9

Mineral Deposits of Alaska

RICHARD J. GOLDFARB AND LANCE D. MILLER, EDITORS



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

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Library of Congress Catalog Card No. 97-060339

Marco T. Einaudi, Editor, Economic Geology,

P.O. Box A-I, Stanford, CA 94309

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 compositing 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.

Contents

Economic Geology
Monograph 9, 1997, pp. 1–3

Mineral Deposits of Alaska

Preface

LANCE D. MILLER

Echo Bay Mines, 3100 Channel Drive, Juneau, Alaska 99801

AND RICHARD J. GOLDFARB

U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado 80225

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 1793 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 1996, 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-Jualin 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 Nikolai 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 east-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 Minehane (1997). The authors integrate new $^{40}Ar/^{39}Ar$ ages with fluid inclusion and stable isotope data to support a model in which low-salinity, CO_2-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 volcanogenic massive sulfide deposits is brought together in the paper by Newberry, Crafford, Newkirk, 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, Coulter, 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 plutons. 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 (1997) describes the igneous-hosted uraniferous 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.

REFERENCES

Ashleman, J.C., Taylor, C.D., and Smith, P.R ., 1997, Porphyry molybdenum deposits of Alaska w ith emphasis on the geology of the Quartz Hill deposit, southeastern Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 334–354.

Bundtzen, T.K., and Miller, M.L., 1997, Precious metals associated with Late Cretaceous-Early Tertiary Igneous Rocks: ECONOMIC GEOLOGY MONOGRAPH 9, p. 242–286.

Foley, J.Y., Light, T.D., Nelson, S.W., and Harris, R.A., 1997, Mineral occurrences associated with mafic-ultramafic and related alkaline complexes: ECONOMIC GEOLOGY MONOGRAPH 9, p. 396–449.

Goldfarb, R.J., 1997, Metallogenic evolution of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 4–34.

Goldfarb, R.J., Miller, L.D., Leach, D.L., and Snee, L.W., 1997, Gold deposits in metamorphic rocks of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 151–190.

Gray, J.E., Gent, C.A., Snee, C.W., and Wilson, F.H., 1997, Epithermal mercury-antimony and gold-bearing vein lodes of southwestern Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 287–305.

Hudson, T.L., and Reed, B.L., 1997, Tin deposits in Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 450–465.

MacKevett, E.M., Cox, D.P., Potter, R.W., II, and Silberman, M.L., 1997, Kennecott-type deposits in the Wrangell Mountains, Alaska: High-grade ores near a basalt-limestone contact: ECONOMIC GEOLOGY MONOGRAPH 9, p. 66–89.

McCoy, D., Newberry, R.J., Layer, P., DiMarchi, J.J., Bakke, A., Masterman, J.S., and Minehane, D.L., 1997, Plutonic-related gold deposits of interior Alaska:ECONOMIC GEOLOGY MONOGRAPH 9, p. 191–241.

Newberry, R.J., Allegro, G.L., Cutler, S.E., Hagen-Levelle, J.H., Adams, D.D., Nicholson, L.C., Weglarz, T.B., Bakke, A.S., Clautice, K.H., Coulter, G.A, Ford, M.J., Myers, G.L., and Szumigala, D.J., 1997a, Skarn deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 355–395.

Newberry, R.J., Crafford, T.C., Newkirk, S.R., Young, L.E., Nelson, S.W., and Duke, N.A., 1997b, Volcanogenic massive sulfide deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 120–150.

Schmidt, J.M., 1997a, Shale-hosted Zn-Pb-Ag and barite deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 35–65.

——1997b, Strata-bound carbonate-hosted Zn-Pb and Cu deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 90–119.

Thompson, T.B., 1997, Uranium, thorium, and rare metal deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 466–482.

Young, L.E., St. George, P., and Bouley, B.A., 1997, Porphyry copper deposits in relation to the magmatic history and palinspastic restoration of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 306–333.

Economic Geology
Monograph 9, 1997, pp. 4–34

Metallogenic Evolution of Alaska

RICHARD J. GOLDFARB

U.S. Geological Survey, Box 25046, Mail Stop 973, Denver Federal Center, Denver, Colorado 80225

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, anorogenic 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-Ellesmerian 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 syngenetic 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 east-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 Craggy, 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 Mesozoic.

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 littoral 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 Klukwan-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 volcano-plutonic 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 convergence 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 Meshik 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; Nokleberg et al., 1987). Descriptive studies of major mineral deposits in northern Alaska were included in a special issue of *Economic Geology* (Einaudi and Hitzman, 1986), 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 shale-hosted base metal deposits (Schmidt, 1997a), 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, shale-hosted deposits of the western 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, 1997b). 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) magmatism, 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 alkalic 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.

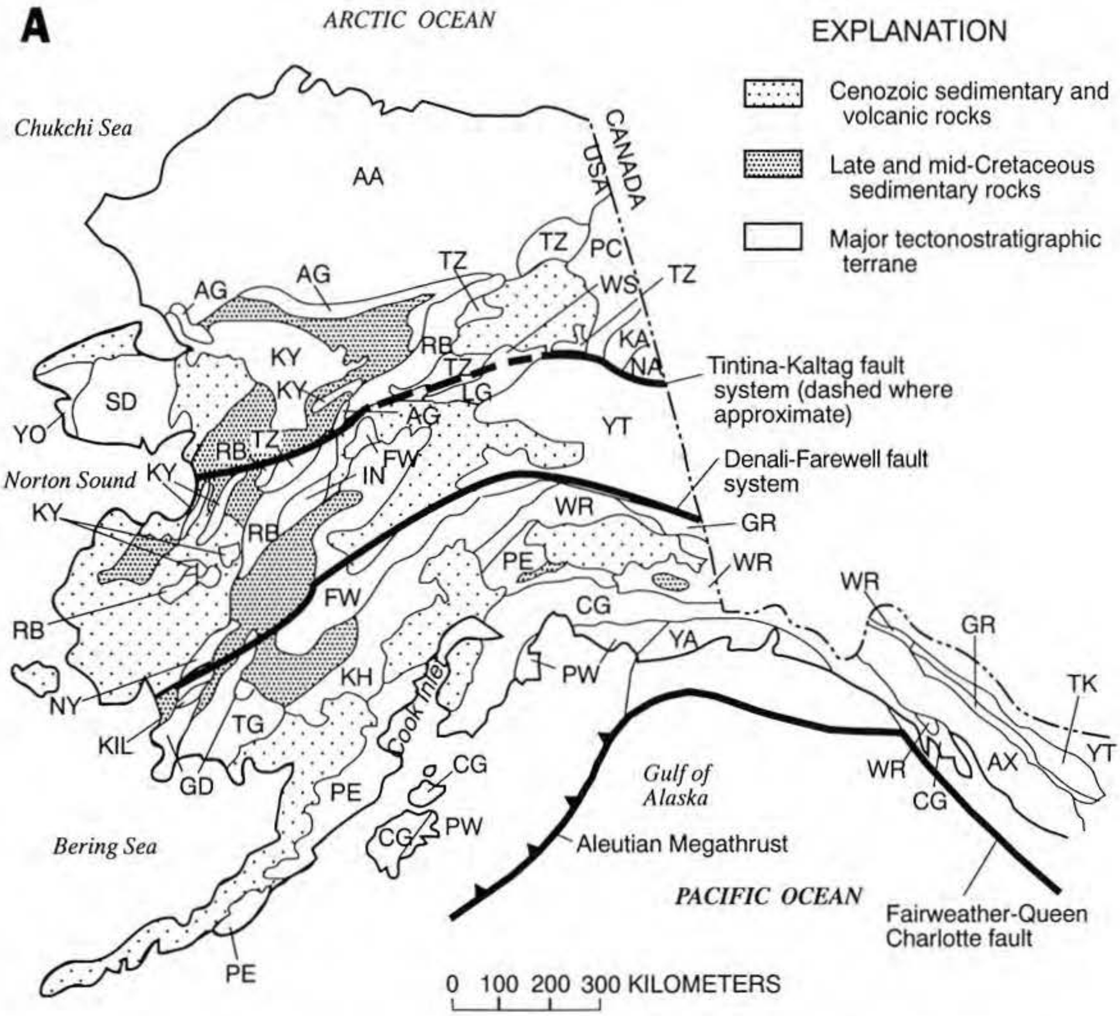


FIG. 1. A. Lithotectonic terrane map of Alaska, generalized from Jones et al. (1987) and Monger and Berg (1987). Terranes and map symbols are as follows: AA = Arctic Alaska, AG = Angayucham, AX = Alexander, CG = Chugach, FW = Farewell, GD = Goodnews, GR = Gravina-Nutzotin overlap assemblage, IN = Innoko, KA = Kandik River, KH = Kahiltna, KIL = Kilbuck, KY = Koyukuk, LG = Livengood, NY = Nyack, PC = Porcupine, PE = Peninsular, PW = Prince William, RB = Ruby, SD = Seward, TG = Togiak, TK = Taku, TZ = Tozitna, WS = Wickersham, WR = Wrangellia, YA = Yakutat, YO = York, YT = Yukon-Tanana. The area labeled NA represents continental rocks of pre-Phanerozoic North America. Also shown are postaccretionary Late and middle Cretaceous sedimentary rocks and Cenozoic sedimentary and volcanic rocks.

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

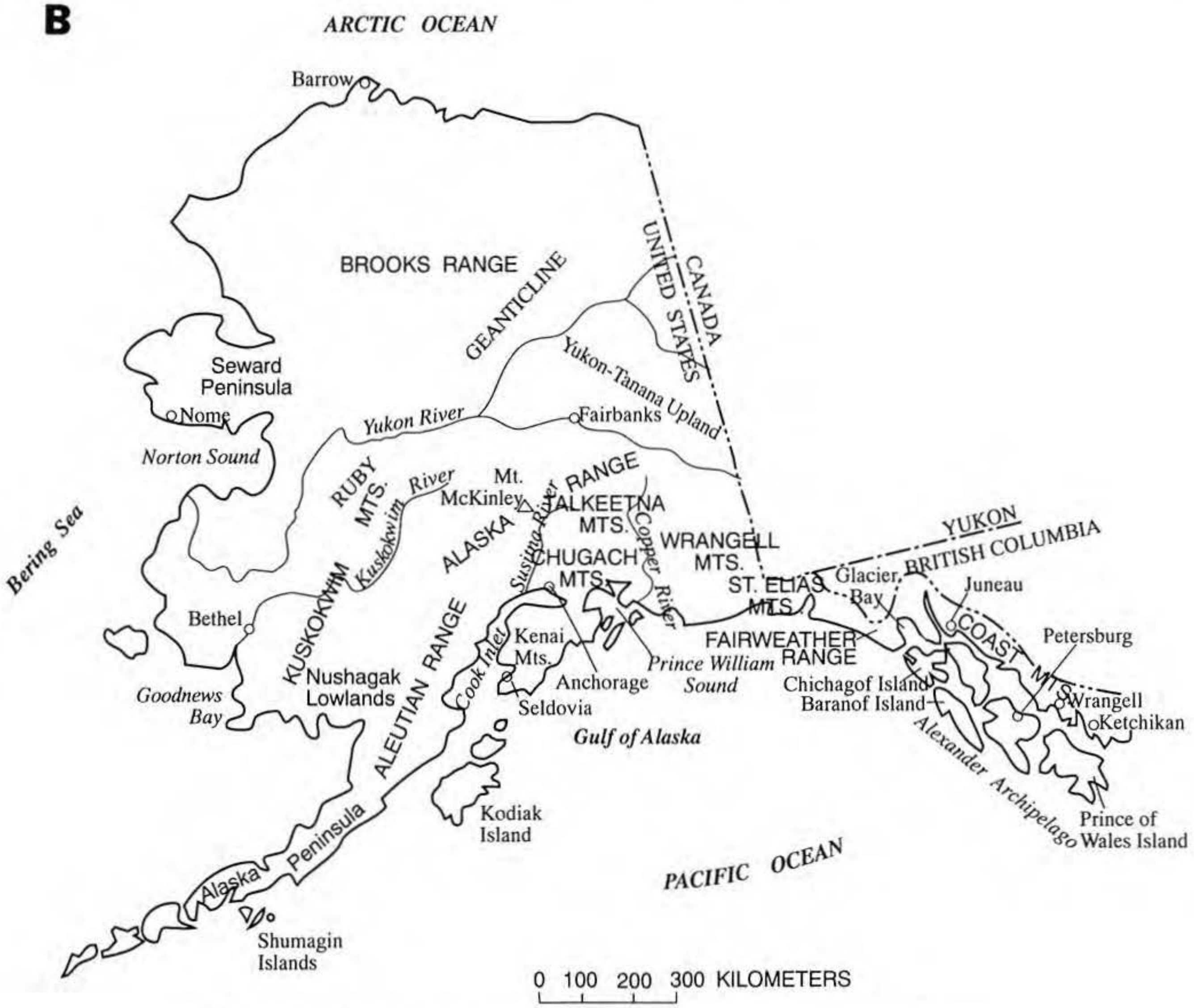


FIG. 1. (*Cont.*). B. Index map of Alaska showing major geographic features discussed in the text.

of the Wrangellia terrane (MacKevett 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 miogeocline (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-

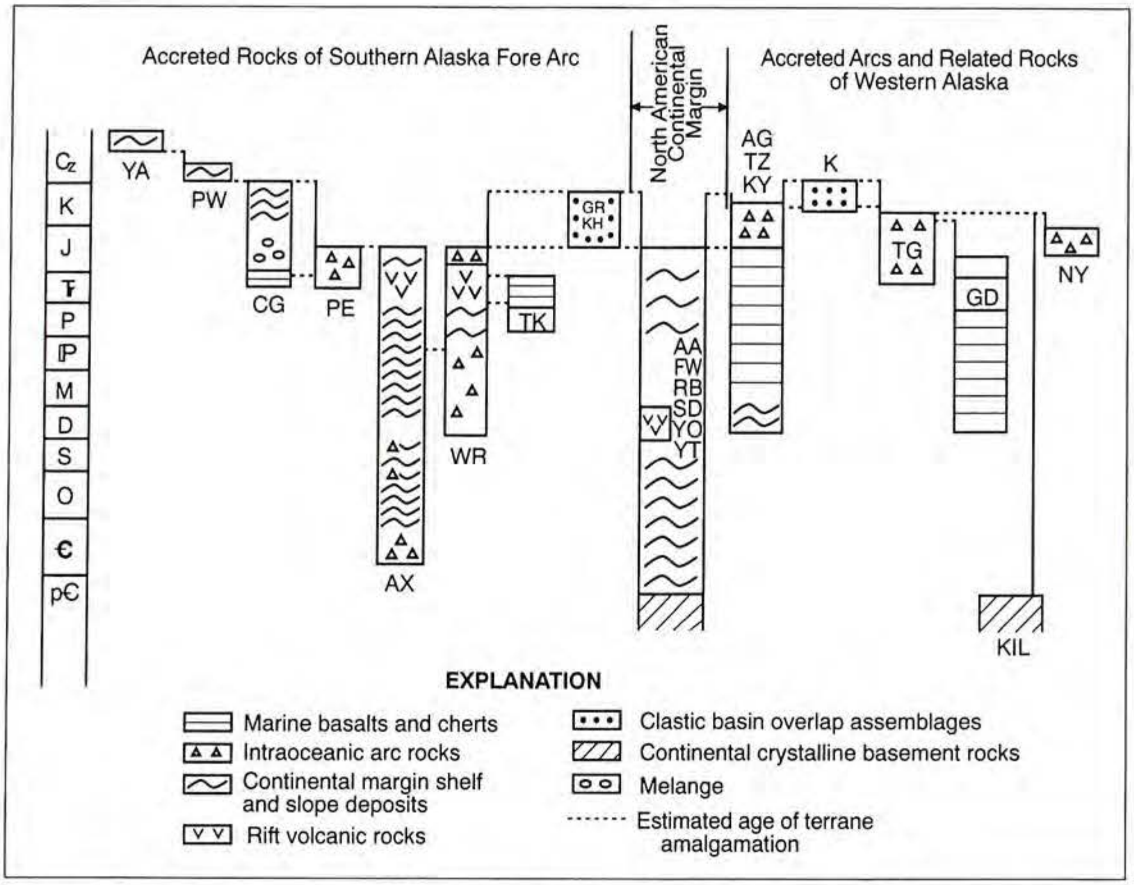


FIG. 2. Temporal history of amalgamation and accretion for major terranes in Alaska. See Figure 1A for abbreviations of terranes.

sive margin and probably rotated away from Arctic Canada during the middle Cretaceous opening of the Arctic Ocean basin (Plafker and Berg, 1994). Possibly, facies-equivalent units in central Alaska that now compose the Farewell terrane were also rifted and rotated away from the Paleozoic cratonic margin. No pre-Devonian metallic mineral occurrences are unequivocally recognized within the continental margin strata of Alaska.

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 correlative with those of the Descon Group have been recognized in the northern part of southeastern Alaska and in northwestern British Columbia (Norford and Mihalynuk, 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 dioritic 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 plugs. Three mines in a 20-km-long mineralized belt have yielded minor amounts of copper, silver, and gold from garnet-pyroxene-epidote-hornblende and magnetite skarn (Warner et al., 1961; Myers, 1984, 1985). Additionally, a small copper porphyry occurrence, the Bug prospect, occurs in part of the dioritic rocks (Young et al., 1997).

The Salt Chuck deposit on Prince of Wales Island is one of a series of Silurian ultramafic-mafic bodies that intruded rocks of the Descon Formation (Loney and Himmelberg, 1992). These bodies may also be part of the early Paleozoic magmatic arc. Production of more than 620 kg of platinum-group metals from the Salt Chuck mine in the early 1900s is the only mining of any ultramafic body in southeastern Alaska. The Salt Chuck orebody is a pipelike replacement deposit in pyroxenite and gabbro and consists of bornite (with subordinate chalcopyrite), precious metals, and secondary copper minerals. Concentration of ore minerals may reflect supergene enrichment rather than primary segregation of metals during pluton emplacement (Berg, 1984).

Devonian through Pennsylvanian

Tectonism associated with Antler (Rubin et al., 1990) and Ellesmerian (Moore et al., 1994) orogenesis included contractional deformation of Proterozoic to middle Paleozoic marine rocks and Devonian arc activity along the craton margin. A Middle to Late Devonian unconformity in the northeastern Brooks Range within both the sedimentary and igneous rocks places an upper age limit on the contractional orogenic event (Moore et al., 1994). Emplacement of some of the Devonian intrusions that crop out in the eastern Brooks Range was associated with minor skarn and porphyry metallogenesis.

An offshore Middle and Late Devonian rifting event began near the end of, or immediately followed, orogenesis. Rotated and displaced fragments of resulting basinal strata in what are now parts of the Brooks Range, east-central Alaska, and southeastern Alaska contain numerous, sometimes large, Devonian through Pennsylvanian volcanogenic massive sulfide and shale-hosted sulfide deposits (Fig. 4).

Newberry et al. (1986b) describe two groups of pluton-related mineral deposits hosted by Early Devonian intrusions and adjacent Early Devonian or older carbonate rocks in the northeastern Brooks Range: (1) metaluminous porphyritic granites and granodiorites, mainly cropping out in the Chandalar area, that are cut by quartz-sericite-pyrite-chalcopyrite stockworks which include sulfide zones containing as much as 0.6 percent Cu, 0.02 percent Mo, and 0.1 ppm Au. These porphyry stockworks are surrounded by a series of small skarn occurrences that zone outward from Cu-Ag rich through Cu-Zn rich to Pb-Zn-Ag rich; and (2) peraluminous granites that are widely scattered in the northeastern Brooks Range and are commonly surrounded by skarns containing Sn-enriched magnetite or garnet. It should be noted that two of the small Zn-Pb skarn occurrences in the eastern Brooks Range are associated with granitic gneiss that could have an age of about 900 Ma (see table 2, no. 53, Newberry et al., 1997b) and therefore could be the oldest mineral deposits recognized in Alaska. Dillon et al. (1980) determined Proterozoic U-Pb and Pb-Pb ages for the gneiss but indicated that middle Paleozoic ages were also possible because of the presence of inherited zircons and an occurrence of a Pb-loss event.

The relationship between the Sn- and base metal-rich magmatic systems is uncertain. The metaluminous 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 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 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 Pennsylvanian 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 58.2 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 Aqqaluk 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 (Forrest, 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 syngenetic, as evidenced by laminated sulfides, vent fauna, monomineralic banding, resedimented 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 diagenesis 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

Mineral deposit	Deposit type	Host terrane	Ore metals
Pre-Devonian			
1. Khayyam-Stumble-On	VMS	AX	Ag, Au, Cu
2. Copper City	VMS	AX	Ag, Au, Cu
3. Niblack	VMS	AX	Ag, Au, Cu
4. Trocadero Bay	VMS	AX	Cu
5. Lime Point	VMS (?)	AX	Ba
6. Kasaan Peninsula district	Fe skarn	AX	Ag, Au, Cu, Fe
7. Salt Chuck	Magmatic	AX	Ag, Au, Cu, Pd
8. Bug	Porphyry	AX	Au, Cu, Mo
Devonian to Carboniferous			
9. Victor-Genroe	Porphyry skarn	AA	Ag, Au, Cu, Mo, Pb, Zn
10. Bear Mountain (?)	Porphyry	AA	Mo
11. Arrigetch Peaks-Mt. Igikpak-Okpilak	Sn skarn	AA	Sn
12. Red Dog	Sediment hosted	AA	Ag, Pb, Zn
13. Lik	Sediment hosted	AA	Ag, Pb, Zn
14. Drenchwater	Sediment hosted	AA	Ag, Pb, Zn
15. Longview-Nimiuktuk	Sedimentary barite	AA	Ba
16. Ginny Ck	Sediment hosted	AA	Ag, Pb, Zn
17. Whoopee Ck	Sediment hosted	AA	Ag, Pb, Zn
18. Story Ck	Sediment hosted	AA	Ag, Pb, Zn
19. Kady-Vidlee	Sediment hosted	AA	Ag, Cu, Pb, Zn
20. Ruby Creek	Carbonate hosted	AA	Cu
21. Omar	Carbonate hosted	AA	Cu
22. Arctic-Sun-Smucker	VMS	AA	Ag, Cu, Pb, Zn
23. Gagaryah	Sedimentary barite	FW	Ba
24. Reef Ridge district	MVT	FW	Pb, Zn
25. Bonnifield district	VMS	YT	Ag, Pb, Zn
26. Trident Glacier	VMS	YT	Ag, Pb, Zn
27. Delta district	VMS	YT	Ag, Au, Cu, Pb, Zn
28. Shellabarger Pass	VMS	FW	Cu, Zn
29. Tracy Arm	VMS	YT	Cu, Zn
30. Sumdum	VMS	YT	Cu, Zn
31. Sweetheart Ridge	VMS	YT	Cu, Zn
Late Triassic			
32. Glacier Creek-Mt. Henry Clay	VMS	AX	Ag, Au, Ba, Cu, Pb, Zn
33. Orange Point	VMS	AX	Ag, Au, Cu, Zn
34. Greens Creek	VMS	AX	Ag, Au, Pb, Zn
35. Pyrola	VMS	AX	Ag, Au, Ba, Pb, Zn
36. Castle Island	Sedimentary barite	AX	Ba
37. Zarembo Island	VMS	AX	Ag, Au, Cu, Pb, Zn
38. Moth Bay-IXL	VMS	TK (?)	Cu, Zn
Jurassic			
39. Iyikrok Mt	Podiform chrome	AG	Cr
40. Avan Hills	Podiform chrome	AG	Cr
41. Misheguk Mountains	Podiform chrome	AG	Cr
42. Siniktanneyak Mt	Podiform chrome	AG	Cr
43. Caribou Mt	Podiform chrome	RB	Cr
44. Kaiyuh Hills	Podiform chrome	RB	Cr
45. Mt. Hurst	Podiform chrome	RB	Cr
46. Johnson River	VMS	PE	Au, Cu, Pb, Zn
47. Red Mt-Claim Point	Podiform chrome	PE	Cr
48. Bernard Mt	Podiform chrome	PE	Cr
49. Eklutna	Podiform chrome	PE	Cr
50. Magnetite Island	Skarn	PE	Fe
51. Chitina Valley batholith	Porphyry	WR	Cu
52. Midas-Berg Creek	Skarn	WR	Ag, Au, Cu, Fe
53. Spirit Mountain	Magmatic Cu-Ni	WR	
54. Bokan Mountain	Magmatic U	AX	REE, U
55. Dora Bay	Magmatic U	AX	REE, U
56. Goodnews Bay	Zoned ultramafic	GD	PGE
57. Kemuk Mt (?)	Zoned ultramafic	TG	Fe, Ti
Mid-Cretaceous			
58. Nome district	Mesothermal vein	SD	Au
59. Chandalar-Koyukuk district	Mesothermal vein	AA	Au
60. Independence	Polymetallic vein	SD	Ag, Pb, Zn
61. Omalik	Polymetallic vein	SD	Ag, Pb, Sb

TABLE 1. (*Cont.*)

Mineral deposit	Deposit type	Host terrane	Ore metals
62. Hannum Creek	Carbonate hosted	SD	Pb, Zn
63. Illinois Creek	Polymetallic vein (?)	RB	Ag, Au, Cu, Pb, Zn
64. Fairbanks-Circle-Fortymile-Hot Springs-Tolvana districts	Mesothermal vein, W skarn	YT	Au, W
65. Roy Creek	Magmatic U	WS	U, REE
66. Ruby district	Sn greisen	RB	Sn
67. Tofty district	Sn greisen	FW	Sn
68. Kennecott district (?)	Carbonate hosted	WR	Ag, Cu
69. Denali (?)	Carbonate hosted (?)	WR	Cu
70. Orange Hill-Bond Ck	Porphyry	WR	Cu, Mo
71. Baultoff-Carl Ck-Horsfeld	Porphyry	GN	Cu
72. Nabesna	Cu skarn	WR	Au, Fe
73. Zackley	Cu skarn	WR	Au, Cu
74. Pebble Copper	Porphyry	KH	Au, Cu
75. Klukwan	Zoned ultramafic	GN	Fe, PGE, Ti
76. Snettisham	Zoned ultramafic	GN	Fe, PGE, Ti, V
77. Union Bay	Zoned ultramafic	GN	Fe, PGE, Ti, V
78. Duke Island	Zoned ultramafic	GN	Fe
79. Red Bluff Bay	Zoned ultramafic (?)	GN (?)	Cr
80. Jumbo	Fe skarn	AX	Ag, Au, Cu
Late Cretaceous			
81. Lost River	Sn griesen-skarn	SD	Be, F, Sn, W
82. Kougarok	Sn greisen-skarn	SD	Sn
83. Cape Mountain	Sn greisen-skarn	SD	Sn
84. Ear Mountain	Sn greisen-skarn	SD	Sn
85. Iditarod-Flat-Innoko districts	Plutonic Au	KK	Au, W
86. Nixon Fork	Au skarn	FW	Ag, Au, Cu
87. Vinasale Mountain	Plutonic Au	KK	Au
88. Beaver Mountains	Plutonic Au	KK	Ag, Au, Cu, Pb
89. Red Devil	Epithermal vein	KK	Hg, Sb
90. Cinnabar Creek	Epithermal vein	KK	Hg
91. White Mountain	Epithermal vein	FW	Hg
92. Kantishna Hills district	Polymetallic vein	YT	Ag, Au, Pb, Sb, Zn
93. Chulitna-Golden Zone	Polymetallic vein, Cu skarn, breccia pipe	CH	Ag, Au, Cu
94. Mt. Estelle	Plutonic Au	KH	Au
95. Midas	VMS	CG	Ag, Au, Cu, Zn
Paleocene and Early Eocene			
96. Taurus	Porphyry	YT	Au, Cu, Mo
97. Asarco	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. Lime Peak	Sn greisen	YT	Sn
103. Kasna Creek	Skarn	PE	Ag, Au, Cu, Fe
104. Crevice Creek	Skarn	PE	Ag, Au, Cu
105. Bonanza Hills	Polymetallic vein	KH	Ag, Au, Cu, Pb
106. Yentna district	Magmatic Sn	KH	Au, Sn
107. Coal Creek	Magmatic Sn	CH	Sn
108. Sleitat Mountain	Magmatic Sn	KK	Sn
109. Valdez Creek district	Mesothermal vein	KH	Au
110. Nuka Bay district	Mesothermal vein	CG	Au
111. Moose Pass district	Mesothermal vein	CG	Au
112. Hope-Sunrise district	Mesothermal vein	CG	Au
113. Girdwood district	Mesothermal vein	CG	Au
114. Port Wells district	Mesothermal vein	CG	Au
115. Port Valdez district	Mesothermal vein	CG	Au
116. Willow Creek district	Mesothermal vein	PE	Au
117. Berns Bay district	Mesothermal vein	WR	Au
118. Alaska Juneau-Treadwell	Mesothermal vein	TK-GN	Au, Ag
119. Sumdum Chief	Mesothermal vein	TK	Au
120. Chichagof district	Mesothermal vein	CG-WR	Au
121. Beatson-Duchess	VMS	PW	Ag, Au, Cu
122. Rua Cove	VMS	PW	Cu, Fe, Zn
123. Schlosser-Threeman	VMS	PW	Ag, Au, Cu, Zn
124. Ellamar	VMS	PW	Ag, Au, Cu, Zn
125. Table Mountain	Porphyry	AA	Mo

TABLE 1. (*Cont.*)

Mineral deposit	Deposit type	Host terrane	Ore metals
Mid-Eocene to Oligocene			
126. Farewell	Zn-Pb skarn	FW	Ag, Cu, Pb, Zn
127. Groundhog Basin	Sn skarn-replacement	YT	Sn, Ag, Pb, Zn
128. Brady Glacier	Magmatic Ni-Cu	CG	Co, Cu, Ni
129. Margerie Glacier	Porphyry	AX	Cu
130. Rendu Glacier	Fe skarn	AX	Ag, Au, Cu, W
131. Alaska Chief	Fe skarn	AX	Ag, Au, Cu
132. Nunatak	Mo skarn	AX	Mo
133. Quartz Hill	Porphyry	YT	Mo
134. Alaska-Apollo	Epithermal vein	PE	Au
135. Shumagin	Epithermal vein	PE	Ag, Au
136. Pyramid	Porphyry	PE	Cu, Mo
137. Bee Creek	Porphyry	PE	Cu, Mo
138. Ivanof	Porphyry	PE	Cu
139. Mike	Porphyry	PE	Mo
140. Rex	Porphyry	PE	Au, Cu

Abbreviations for most host terranes are listed in Figure 1A; also KK = the Cretaceous sedimentary rocks of the Kuskokwim basin, CH = the Chulitna terrane of Jones et al. (1987). MVT = Mississippi Valley type. VMS = volcanogenic massive sulfide; (?) = uncertain age of deposit, deposit type, or host terrane

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 Werdon, 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., 1993). 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 Vidlee (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., 1980; 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, 1989). However, no additional significant volcanogenic massive sulfide prospects are known outside the Ambler 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 Hannum 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 Hannum 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.

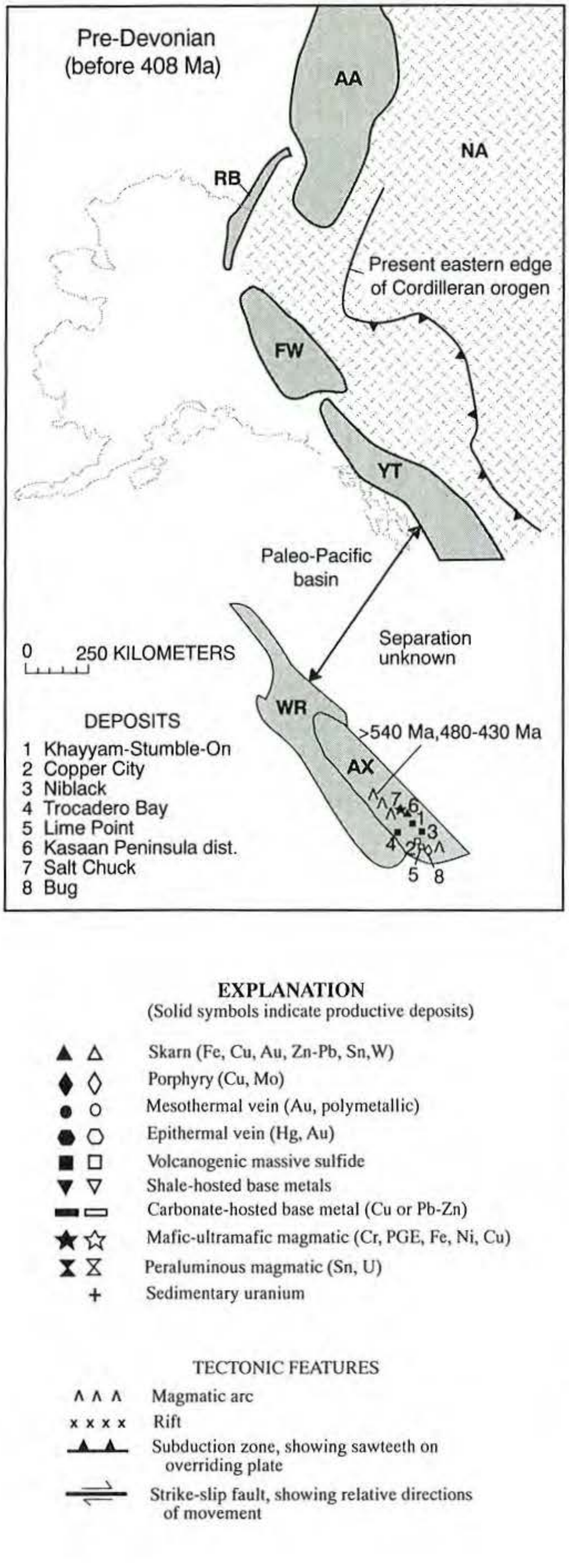
The Ruby geanticline is a pre-middle Cretaceous uplift that trends diagonally across central Alaska, striking southwesterly from the southeastern edge of the Brooks Range (Fig. 1B). Lithologic and metamorphic similarities between sedimentary rocks of the geanticline and those of the southern Brooks Range have led to the suggestion that the Ruby geanticline is a counterclockwise- (Patton, 1970) or clockwise-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 Kechika 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 Gagaryah barite deposit in southwestern Alaska. The deposit occurs in Middle to early Late Devonian siltstone and shale at the base of the Mystic sequence of the Farewell terrane along the south side of the Denali fault system. It is significant because it indicates a second region within Alaska favorable for large, shale-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 Kechika 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 hinders reasonable palinspastic 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 submarine, continental margin igneous-arc magmatism above a north- to 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 subterranes 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-dominant pods, lenses, and stringers are hosted by felsic to 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 Devono-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 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 orthogneiss 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 Moth 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 southeastern 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 basinal strata and associated bimodal volcanic rocks that unconformably overlies 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,

FIG. 3. Paleogeographic reconstruction of lithotectonic terranes of northwestern North America in pre-Devonian time in relation to the present location of Alaska screened outline. The only definite pre-Devonian mineral deposits known in Alaska are precious metal-bearing volcanic massive sulfide, bedded barite, and Fe-Cu-Au skarns formed in southern Alexander terrane distal to North America. Ore deposition was coeval with Late Proterozoic(?) to Cambrian and Middle Ordovician to middle Early Silurian arc-type magmatism (Gehrels and Saleeby, 1987). Inferred terrane configuration from Plafker and Berg (1994). Solid symbols indicate productive deposits. The Explanation applies to Figures 3–10.

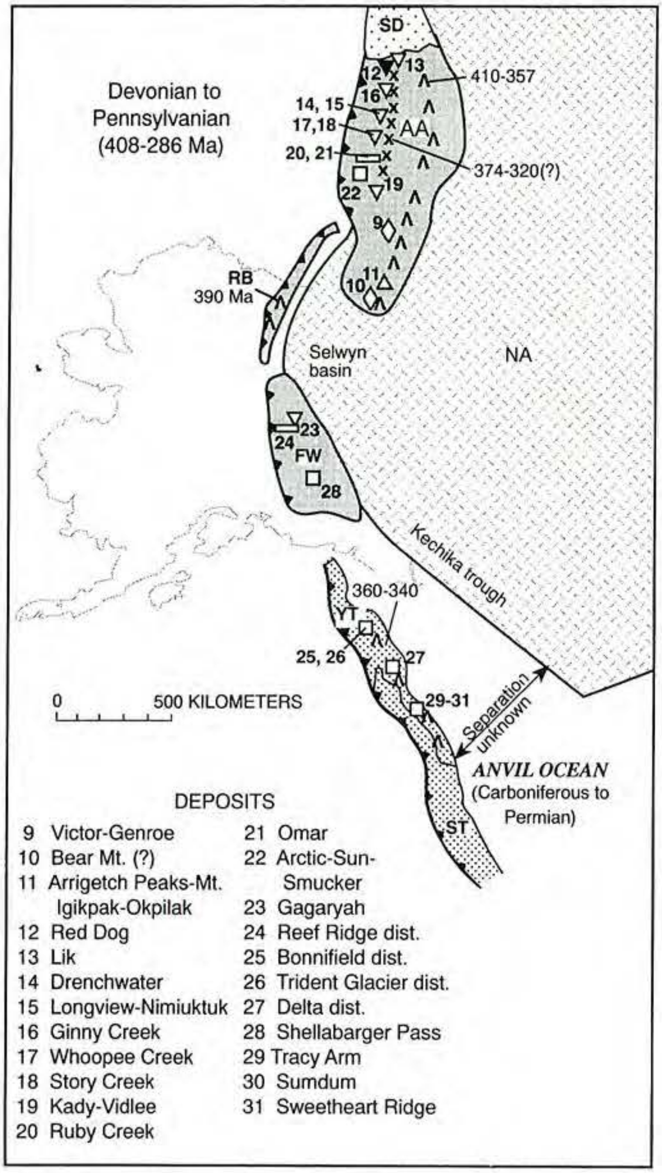


FIG. 4. Mineral deposits of Late Devonian and Mississippian age formed along the passive northwestern margin of the North American craton. Shale-hosted massive sulfide, carbonate-hosted copper, and Cu-Zn-rich volcanogenic massive sulfide deposits formed in the northern part of the Arctic Alaska terrane during probable rifting; small porphyries 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 terrane configuration from Plafker and Berg (1994). See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.

period of volcanogenic massive sulfide formation within this accreted terrane, which forms a major part of southeastern Alaska.

Volcanogenic massive sulfide deposits associated with 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 basalt 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, 1991). 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

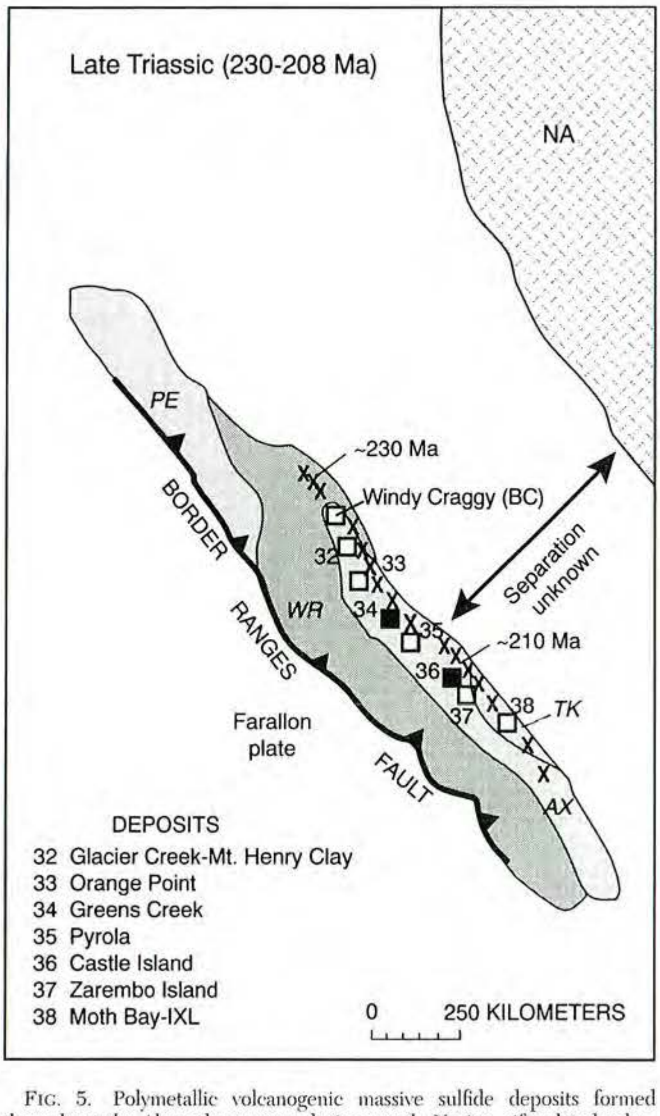


FIG. 5. Polymetallic volcanogenic massive sulfide deposits formed throughout the Alexander terrane during mostly Norian, rift-related volcanism within an intraoceanic microcontinent. Extrusion of a thick sequence of subaerial and shallow-marine flood basalts in the adjoining Wrangellia terrane occurred in Carnian time. Inferred terrane configuration from Plafker 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 clastic units, mafic volcanic rocks, and metarhyolite(?) (Berg and Grybeck, 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 $^{40}Ar/^{39}Ar$ 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 Grybeck, 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 superterrane and was located far from the present North American cratonic margin (Plafker et al., 1989b). Tholeiitic basalts in the Wrangellia and Taku terranes (Plafker 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 (Plafker 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 paleomagnetic 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 Togiak 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.

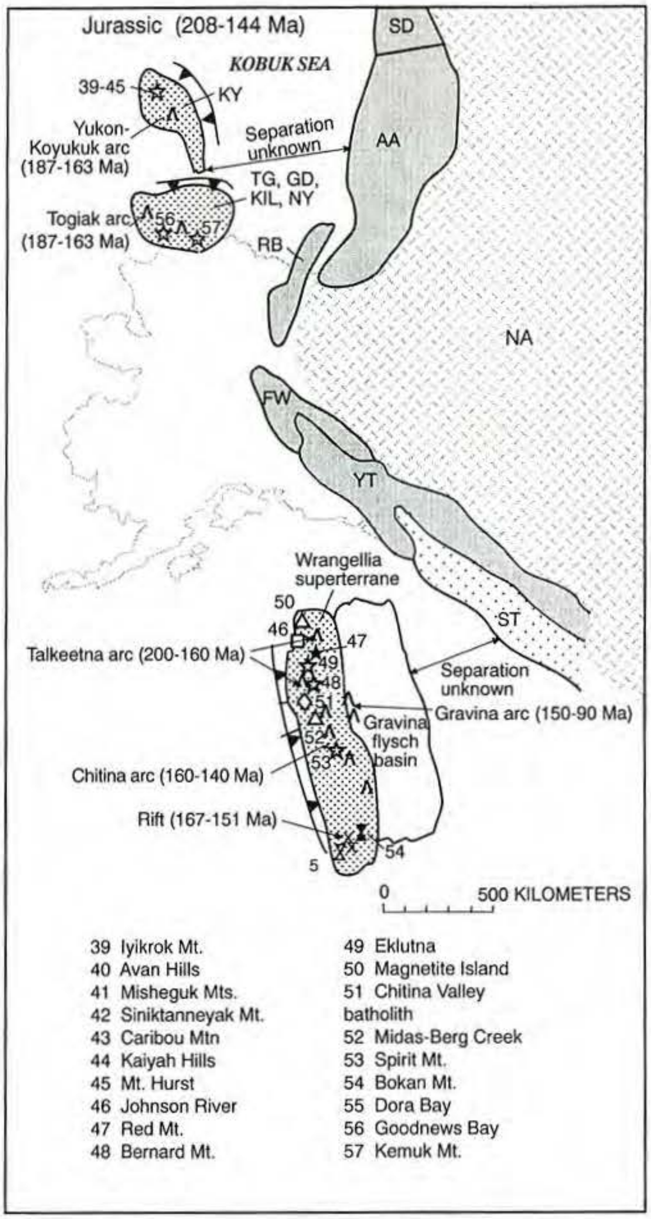


FIG. 6. The Jurassic period featured intraoceanic arc magmatism and distribution of rifted continental fragments across the Pacific Ocean basin. Magmatic activity led to formation of deposits of podiform chromite, precious metal-bearing volcanogenic massive sulfide, and iron skarns in the Talkeetna arc (Peninsular terrane of the Wrangellia superterrane); copper porphyry, copper skarn, and magmatic Ni-Cu in the Chitina arc (Wrangellia terrane); podiform chromite in the Yukon-Koyukuk arc (Angayucham terrane); and PGE-enriched zoned ultramafic complexes in the Togiak arc (Togiak and Goodnews terranes). Alaska's only past uranium producer, the Bokan Mountain deposit, developed during intrusion of peralkaline rocks in what is now the southern part of the Alexander terrane. Inferred terrane configuration from Wallace et al. (1989) and Plafker and Berg (1994). See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.

Arc magmatism produced podiform chromite 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. Magmatic events, perhaps products of local extensional episodes, also led to Middle Jurassic emplacement of PGE-rich, Alaska-type zoned ultramafic complexes in the Togiak 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 Tethyan-type ophiolites host podiform chromite occurrences containing anomalous PGE concentrations (Foley et al., 1997). An estimated 0.7 to 2.3 Mt of Cr_2O_3 are contained in 70 occurrences at Iyikrok Mountain, Avan Hills, Misheguk Mountain, and Siniktanneyak 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, Kaiyuh Hills, Mount Hurst, and elsewhere throughout the Ruby geanticline. If the geanticline was a geologic extension of the southern 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 volcanic rocks of the Goodnews terrane were subducted below and accreted to the northwestern edge of the Togiak 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 Alaska-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 placers 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 dunite (Foley, 1992), but few lode occurrences have been found in the ultramafic bodies. This means either that the PGE are very finely disseminated or that the source lodes have since been eroded (Mertie, 1976).

The Kemuk Mountain iron deposit, which has reserves of 2,200 Mt of 15 to 17 percent Fe, 2 to 3 percent TiO_2, and 0.16 percent P_2O_5 (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., unpub. company report, 1959). The igneous complex, drilled in the late 1950s because of its aeromagnetic expression, and rocks of the surrounding Togiak 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 Togiak and Goodnews terranes were amalgamated into a single arc complex by that time, and the ultramafic bodies at Goodnews Bay and Kemuk 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 gabbronorite, 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 magmas 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 mélange 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, metalliferous 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 (Steefel, 1987) represents the only recognized significant volcanogenic massive sulfide system formed during this hydrothermal episode. Gold- and base metal-rich quartz stockworks cut volcaniclastic 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 Cr_2O_3 is in 42 deposits hosted by the ophiolitic complex (Foley 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 Cr_2O_3 and 0.1 Mt of material averaging more than 20 percent Cr_2O_3; the adjacent Windy River placer contains 0.5 Mt of material averaging 1.33 percent Cr_2O_3 (Foley et al., 1985). The only chromite mined in Alaska, about 0.03 Mt of 40 percent Cr_2O_3 (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 (Roeske 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 (Moffit 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 U_3O_8 and 3 percent ThO_2 (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

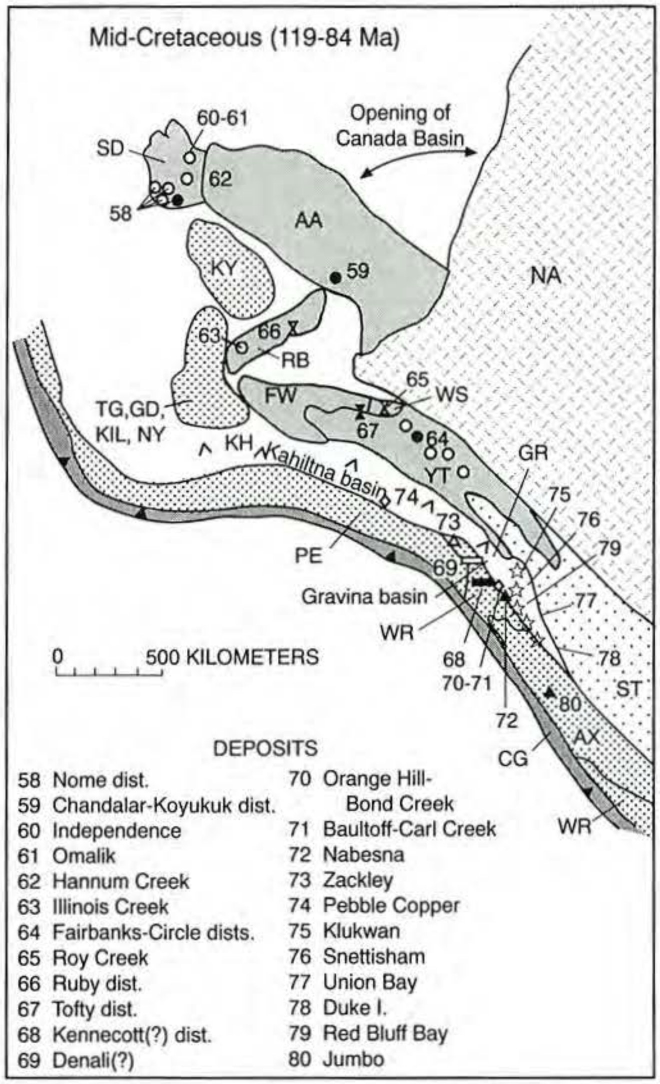


FIG. 7. The middle Cretaceous in Alaska was characterized by a major gold-forming event in the Seward and Yukon-Tanana terranes and by the formation of a variety of pluton-related mineral deposits in the Wrangellia superterrane and the adjacent landward flysch basin. Inferred terrane configuration from Plafker and Berg (1994). See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.

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 flysch 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 time.

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 oroclinal bend of southern Alaska and as part of the Kahiltna 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 volcanogenic 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 orogenesis 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 Omalik 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 (Foster 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., 1990). 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 rocks. 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 89 ± 1 Ma cut porphyritic 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, K feldspar from a mineralized intrusion has been dated at 87 Ma (Bundtzen and Reger, 1977).

Gold- and cassiterite-bearing placer deposits are widespread in central Alaska and are spatially associated with granite and, less often, with granodiorite, monzonite, and syenite of the Ruby batholith dated at 112 to 105 Ma (R. Newberry, written commun., 1995). The placer deposits include those of the Ruby district in the Ruby geanticline and the Tofty district in the adjacent flyschoid rocks of the Manley terrane (Jones et al., 1987). Additionally, about 60 t of niobium oxide was recovered from placers in the Tofty district (Warner, 1985). Source lodes for the placers have been mainly eroded away, but Warner (1985) noted the presence of Sn-bearing greisen in the Sithylemenkat 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., 1995), 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 miogeocline 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 (Woodsworth 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 arc 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 this 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 Kahiltna 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 porphyritic granodiorite in the complex led to widespread distribution of sulfide-rich stockwork veinlets. 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 terrane 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 chalcocite 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. As temperature waned, bornite was replaced by massive chalcocite. 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 superterrane 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 chalcocite did not occur until long after accretion of the superterrane, 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-dominant 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, correlative Karmutsen 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 orebodies. 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 arc magmatism along southeastern Alaska. Between 110 and 90 Ma, plutons ranging in composition from ultramafic to leucogranodioritic intruded rocks of the amalgamated Wrangellia, 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-Revillagigedo belt of calc-alkaline intrusions (Brew and Morrell, 1983). Emplacement of these syndeformational 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 superterrane (Berg et al., 1972). They were emplaced during final closure of the Gravina flysch basin, which juxtaposed rocks of the Wrangellia superterrane 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 superterrane and the continental margin backstop (Saleeby, 1992). Taylor and Noble (1969) suggested that the bodies formed by multiple injections of crystallizing ultramafic magmas. Irvine (1974), however, suggested that each complex formed during a single crystal-settling 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 diopsidic 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 (Still, 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 Descon 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 volcaniclastic 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 (Plafker 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-Stalcup, 1994). The resulting subduction-related arc, active through Eocene time, is at least 150 km wide and extends along a northeasterly trend from the northern part of the Alaska Peninsula to near Mount McKinley. Coeval magmatism, perhaps part of a single widespread event (Moll-Stalcup, 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). Gold-bearing, generally polymetallic 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

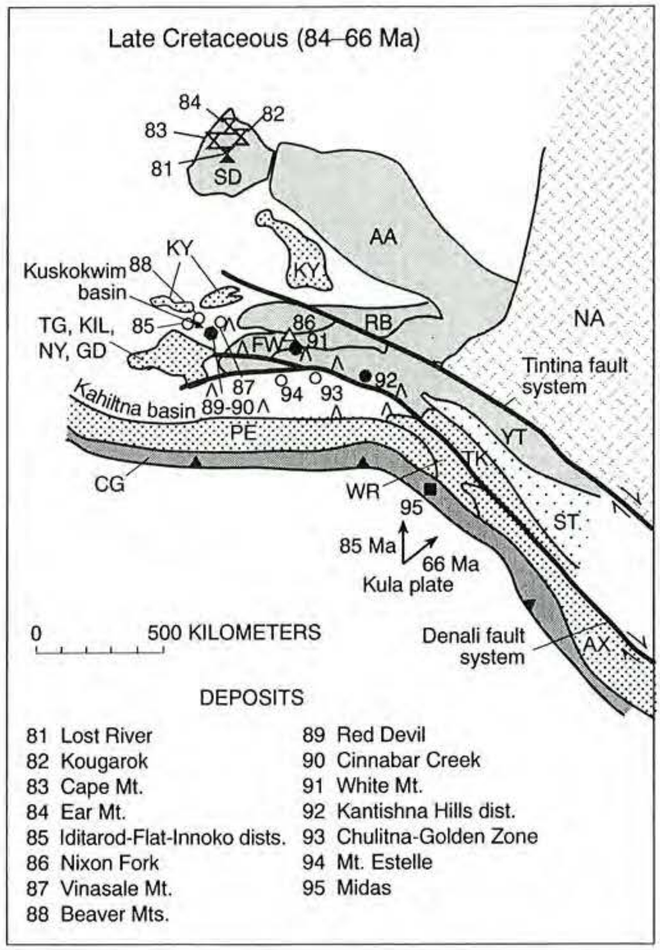


FIG. 8. Late Cretaceous time in Alaska was marked by anorogenic magmatism yielding tin- and uranium-rich rocks in the north; by magmatic-arc activity in southwestern Alaska that drove pluton-related gold-vein and mercury-rich epithermal-vein formation; and by sea-floor volcanism south of the continental 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.

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 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-axinite-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 WO_3 (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 (Sainsbury, 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 veinlets 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 900 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 veinlets 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-km^2 Kuskokwim 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 arc magmas generated in a mantle wedge. This suggests that plutons of the Kuskokwim 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., 1994) and is Alaska's third most productive placer camp. Many productive placers in the Kuskokwim 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 Kuskokwim 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, Vinasale Mountain, and Beaver Mountains occurrences, believed to approximate the time of metallic mineralization, range between 70 and 65 Ma (Szumigala, 1993). One $^{40}Ar/^{39}Ar$ 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 (Szumigala, 1993).

Epithermal cinnabar and/or stibnite vein systems are also scattered throughout southwestern Alaska. They include the Red Devil mine, which produced 35,000 flasks 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 Kuskokwim basin, perhaps during localized devolatilization associated with emplacement of igneous bodies (Goldfarb et al., 1990). A $^{40}Ar/^{39}Ar$ 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 Kuskokwim 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 gabbroic dikes that have a hornblende K-Ar age of 81.3 Ma (Bundtzen and Turner, 1978).

The Alaska Range-Talkeetna Mountains magmatic arc formed landward of the Wrangellia superterrane and south and east of the Kuskokwim 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 (Crowe 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.

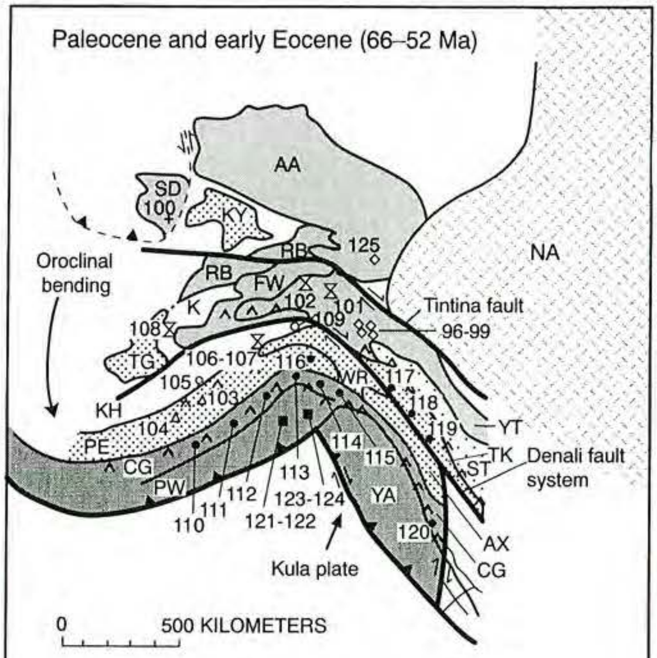
Initiation of sea-floor volcanism, perhaps associated with spreading along the Kula ridge near the triple junction of the Kula, Farallon, and the North America plates, led to a 15- to 30-m.y.-long period of Fe-Cu-Zn-rich volcanogenic massive sulfide formation. The resulting Cyprus- and Besshi-type deposits 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., 1994). The Midas 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 t Cu with grades of 3.4 percent Cu and 1.5 g/t Au (Crowe 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 t of 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 Yukon-Tanana terrane north of the Alaska Range and within about 25 km of the Canadian border. Chalcopyrite and molybdenite in stockworks and as disseminations occur in highly altered granite-porphyry, granodiorite, and quartz latite-porphyry. All recognized porphyry systems are associated with subvolcanic intrusions, are surrounded by large alteration halos, have a pyrite-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



DEPOSIT

96	Taurus	111	Moose Pass dist.
97	Asarco	112	Hope-Sunrise dist.
98	Bluff	113	Girdwood dist.
99	Mosquito	114	Port Wells dist.
100	Death Valley	115	Port Valdez dist.
101	Circle dist.	116	Willow Creek dist.
102	Lime Peak	117	Berners Bay dist.
103	Kasna Creek	118	Alaska-Juneau-Treadwell
104	Crevice Creek	119	Sumdum Chief
105	Bonanza Hills	120	Chichagof dist.
106	Yentna dist.	121	Beatson-Duchess
107	Coal Creek	122	Rua Cove
108	Sleitat Mountain	123	Schlosser-Threeman
109	Valdez Crk dist.	124	Ellamar
110	Nuka Bay dist.	125	Table Mountain

FIG. 9. During early Tertiary fore-arc and arc magmatism, mesothermal gold veins formed throughout accreted terranes of southeastern and south-central Alaska, and tin greisens and base metal-rich skarns formed in southwestern Alaska. To the south, copper-rich volcanogenic massive sulfide deposits continued to develop in the Pacific basin, and to the north, a large sandstone-hosted uranium deposit developed on the Seward Peninsula. 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.

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, 1986) 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 marble 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 (Richter 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 monzodiorite (Nelson et al., 1983).

Tin-bearing mineral occurrences are associated with some of the younger, peraluminous plutons of the Alaska Range arc. These metalliferous 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 superterrane 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 granitic 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 greisen of about 57 Ma within the Sleitat 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 greenschist 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 greenschist 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 $^{40}Ar/^{39}Ar$ 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 t Au were recovered from mesothermal veins cutting a 79 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 $^{40}Ar/^{39}Ar$ 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 Orca 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 (Plafker 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 metalliferous 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 (Plafker 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 Plafker (1981) suggested a similar age for crystallization of the Crillon-La Perouse (gabbro) pluton in the Fairweather Range. A $^{40}Ar/^{39}Ar$ date of 30 Ma for biotite from a pegmatite dike cutting the Crillon-La Perouse 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 Perouse 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 (Bundtzen 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 monzonite-porphyry 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, metalliferous 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.

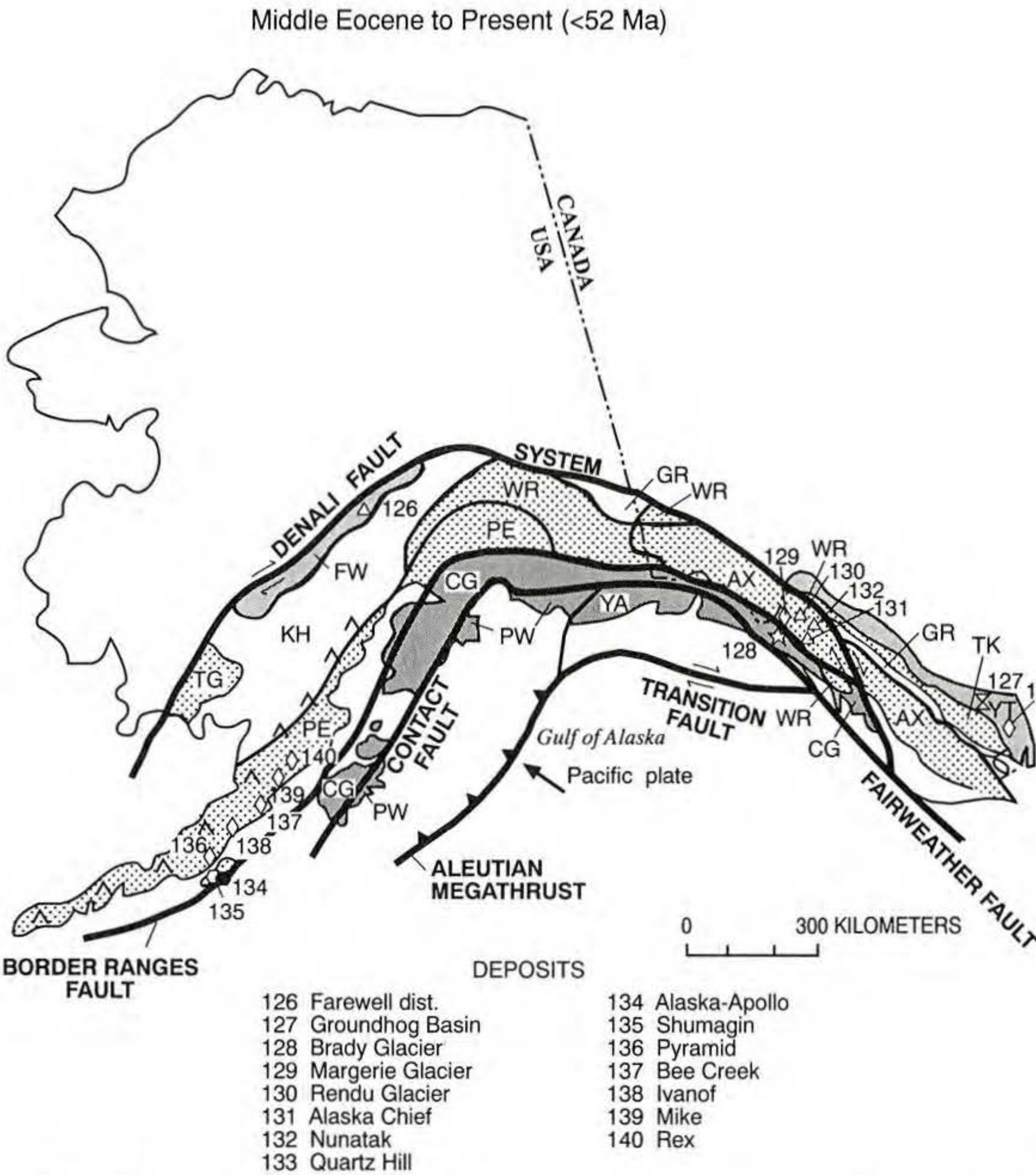


FIG. 10. The last 50 m.y. in southeastern Alaska have been characterized by formation of gabbroic Ni-Ci and copper and molybdenum porphyries and skarns. Initiation of Aleutian arc magmatism produced porphyry copper deposits and epithermal gold veins. See Figure 1A for abbreviations of terranes, Figure 3 for symbols of deposit type and tectonic features.

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 Meshik 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 chalcocite 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 39 to 34 Ma. This suggests that more gold-rich hydrothermal systems may be associated with the older Meshik 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 breccia 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., 1995). 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 podiform 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 metalliferous 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-

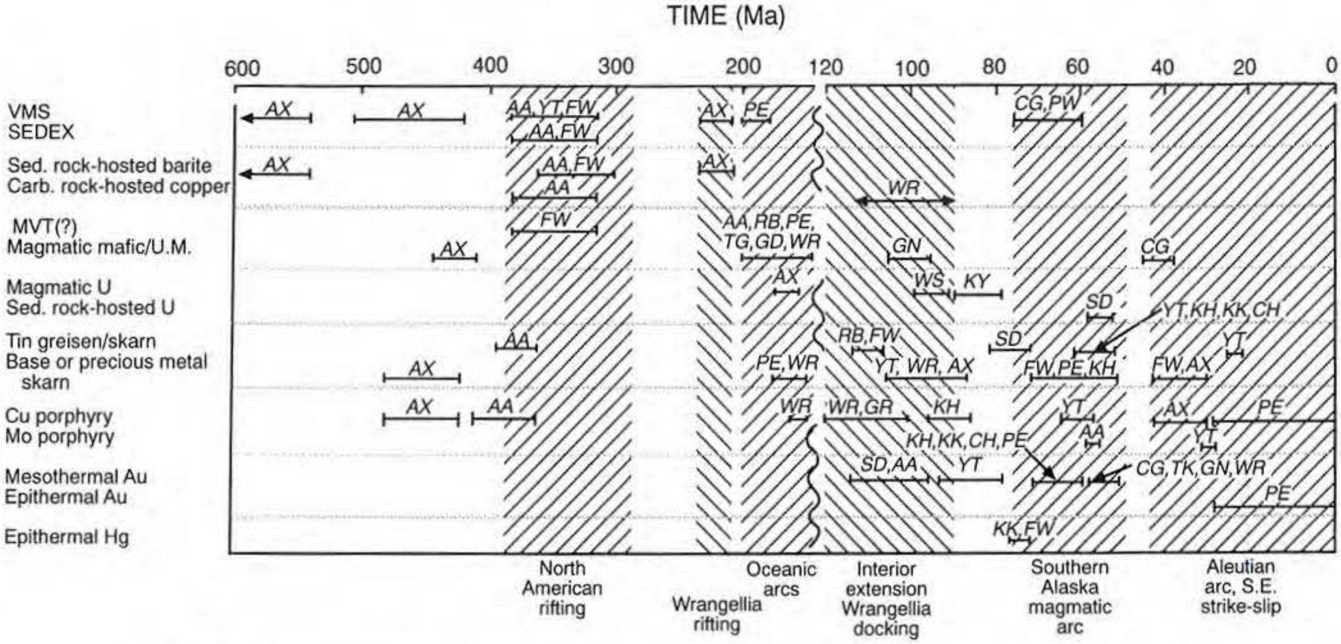


FIG. 11. Summary of the metallogenic evolution of Alaska. Between about 600 and 150 Ma, metallogenic episodes were restricted mainly to intraoceanic environments. From about 120 Ma to the present, subduction-related tectonism has directed most of the metalliferous ore-forming activity. Abbreviations: Carb. = carbonate, MVT = Mississippi Valley type, Sed. = sedimentary, SEDEX = sedimentary exhalative, U.M. = ultramafic, VMS = volcanogenic massive sulfide. See Figure 1A for abbreviations of terranes.

ronments 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 Wrangellia, 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 deposits 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 Wrangellia 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.

Acknowledgments

This paper benefited from careful reviews by H. Berg, T. Hudson, D. Leach, M. Miller, R. Newberry, L. Young, and two *Economic Geology* referees. I am grateful to G. Plafker for a preprint of his manuscript on the tectonic reconstruction

of Alaska, which provided a basis for looking at the metallogeny of Alaska throughout the Phanerozoic.

REFERENCES

Adams, D.D., Freeman, C.J., Goldfarb, R.J., Gent, C.A., and Snee, L.W., 1992, Age and geochemical constraints on mesothermal gold mineralization, Valdez Creek district, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 24, p. 2.

Apodoca, L.E., 1994, Genesis of lode gold deposits of the Rock Creek area, Nome mining district, Seward Peninsula, Alaska: Unpublished Ph.D. dissertation, Boulder, Colorado, University of Colorado, 208 p.

Armstrong, A.K., and MacKevett, E.M., Jr., 1976, Relations between Triassic carbonate sabkhas and Kennecott-type copper deposits: U.S. Geological Survey Circular 733, p. 50–51.

Armstrong, R.L., 1985, Rb-Sr dating of the Bokan Mountain granite complex and its country rocks: Canadian Journal of Earth Sciences, v. 22, p. 1233–1236.

Armstrong, R.L., Harakal, J.E., Forbes, R.B., Evans, B.E., and Thurston, S.P., 1986, Rb-Sr and K-Ar study of metamorphic rocks of the Seward Peninsula and southern Brooks Range, Alaska: Geological Society of America Memoir 164, p. 185–203.

Ashleman, J.C., Taylor, C.D., and Smith, P.R., 1997, Porphyry molybdenum deposits of Alaska with emphasis on the geology of the Quartz Hill deposits, southeastern Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 334–354.

Barker, J.C., and Mardock, C., 1990, Rare earth element- and yttrium-bearing pegmatite dikes near Dora Bay, southern Prince of Wales Island: U.S. Bureau of Mines Open-File Report 19–90, 41 p.

Barker, J.C., and Swainbank, R.C., 1986, A tungsten-rich porphyry molybdenum occurrence at Bear Mountain, northeast Alaska: ECONOMIC GEOLOGY, v. 81, p. 1753–1759.

Berg, H.C., 1984, Regional geologic summary, metallogenesis, and mineral resources of southeastern Alaska: U.S. Geological Survey Open-File Report 84–572, 298 p.

Berg, H.C., and Cobb, E.H., 1967, Metalliferous lode deposits of Alaska: U.S. Geological Survey Bulletin 1256, 254 p.

Berg, H.C., and Grybeck, D., 1980, Upper Triassic volcanogenic Zn-Pb-Ag (-Cu-Au)-barite mineral deposits near Petersburg, Alaska: U.S. Geological Survey Open-File Report 80–527, 9 p.

Berg, H.C., Jones, D.L., and Richter, D.H., 1972, Gravina-Nutzotin belt: Tectonic significance of an upper Mesozoic sedimentary and volcanic sequence in southern and southeastern Alaska: U.S. Geological Survey Professional Paper 800-D, p. D1–D24.

Bouley, B.A., St. George, P., and Wetherbee, P.K., 1995, Geology and discovery at Pebble Copper, a copper-gold porphyry system in southwest Alaska: Canadian Institute of Mining, Metallurgy, and Petroleum Special Volume 46, p. 422–435.

Box, S.E., 1985, Early Cretaceous orogenic belt in northwestern Alaska: Internal organization, lateral extent, and tectonic interpretation: Circum-Pacific Council for Energy and Mineral Resources, Earth Sciences Series, v. 1, p. 137–145.

Bradley, D.C., Haeussler, P.J., and Kusky, T.M., 1993, Timing of early Tertiary ridge subduction in southern Alaska: U.S. Geological Survey Bulletin 2068, p. 163–177.

Brew, D.A., 1988, Latest Mesozoic and Cenozoic magmatism in southeastern Alaska: A synopsis: U.S. Geological Survey Open-File Report 88–405, 29 p.

Brew, D.A., and Morrell, R.P., 1983, Intrusive rocks and plutonic belts of southeast Alaska, U.S.A.: Geological Society of America Memoir 159, p. 171–193.

Brew, D.A., Johnson, B.R., Grybeck, D.J., Griscom, A., and Barnes, D.F., 1978, Mineral resources of the Glacier Bay National Monument Wilderness study area, Alaska: U.S. Geological Survey Open-File Report 78–494, 670 p.

Bundtzen, T.K., 1988, Kantishna district: U.S. Geological Survey Open-File Report 88–73, p. 25–26.

Bundtzen, T.K., and Gilbert, W.G., 1991, Geology and geochemistry of the Gagaryah barite deposit, western Alaska Range, Alaska: Alaska Division of Geological and Geophysical Surveys Professional Report 111, p. 9–20.

Bundtzen, T.K., and Miller, M.L., 1997, Precious metals associated with Late Cretaceous-early Tertiary igneous rocks of southwestern Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 242–286.

Bundtzen, T.K., and Reger, R.D., 1977, The Richardson lineament: A structural control for gold deposits in the Richardson mining district, interior Alaska: Alaska Division of Geological and Geophysical Surveys Report 55, p. 29–34.

Bundtzen, T.K., and Turner, D.L., 1978, Geochronology of metamorphic and igneous rocks in the Kantishna Hills, Mount McKinley quadrangle, Alaska: Alaska Division of Geological and Geophysical Surveys Geologic Report 61, p. 25–30.

Bundtzen, T.K., Kline, J.T., Smith, T.E., and Albanese, M.D., 1988, Geology of the McGrath A-2 quadrangle: Alaska Division of Geological and Geophysical Surveys Professional Report 91, 22 p., scale 1:63,360.

Bundtzen, T.K., Swainbank, R.C., Clough, A.H., Henning, M.W., and Hansen, E.W., 1994, Alaska's mineral industry 1993: Alaska Division of Geological and Geophysical Surveys Special Report 48, 84 p.

Burleigh, R.C., 1991, Geology of the Sleitat tin deposit, southwest Alaska: Alaska Division of Geological and Geophysical Surveys Professional Report 111, p. 29–39.

Burns, L.E., 1985, The Border Ranges ultramafic and mafic complex, south-central Alaska: Cumulate fractionate of island arc volcanics: Canadian Journal of Earth Sciences, v. 22, p. 1020–1038.

Burton, P.J., 1981, Radioactive mineral occurrences, Mount Prindle area, Yukon-Tanana uplands, Alaska: Unpublished M.S. thesis, Fairbanks, Alaska, University of Alaska, 72 p.

Chipp, E.R., 1988, Taurus Cu-Mo deposit: U.S. Geological Survey Open-File Report 88–73, p. 23–24.

Church, S.E., Briskey, J.A., Delavaux, M.H., and LeHuray, A.P., 1985, Preliminary results of Pb-isotope analyses of deposits from the Seward Peninsula: U.S. Geological Survey Circular 967, p. 24–27.

Church, S.E., Gray, J.E., Delavaux, M.H., and LeHuray, A.P., 1987, Pb-isotope signatures of Devonian-Mississippian massive sulphide deposits in Alaska and their significance to mineral exploration, *in* Elliot, I.L., and Smee, B.W., eds., Geoexo/86: Exploration in the North American cordillera: Rexdale, Ontario, Association of Exploration Geochemists, p. 132–141.

Church, S.E., Detterman, R.L., and Wilson, F.H., 1989, Mineral and energy resource assessment maps of the Ugashik, Bristol Bay, and western Karluk quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1539-I, scale 1:250,000.

Cobb, E.H., 1973, Placer deposits of Alaska: U.S. Geological Survey Bulletin 1374, 213 p.

Cobb, E.H., and Kachadoorian, R., 1961, Index of metallic and nonmetallic mineral deposits of Alaska compiled from published reports of federal and state agencies through 1959: U.S. Geological Survey Bulletin 1139, 363 p.

Cohen, H.A., and Lundberg, N., 1993, Detrital record of the Gravina arc, southeastern Alaska: Petrology and provenance of the Seymour Canal Formation sandstones: Geological Society of America Bulletin, v. 105, p. 1400–1414.

Crafford, T.C., 1989, The Greens Creek Ag-Au-Pb-Zn massive sulfide deposit, Admiralty Island, southeast Alaska [abs.]: Alaska Miners Association Conference, Juneau, Alaska, April 1989, Abstracts of Professional Papers, p. 27–29.

Crowe, D.E., Millholland, M.A., and Brown, P.E., 1990, High-grade gold mineralization associated with high-salinity hydrothermal fluids, Mount Estelle pluton, central Alaska Range [abs.]: Geological Society of America Abstracts with Programs, v. 22, p. A41.

Crowe, D.E., Nelson, S.W., Brown, P.E., Shanks, W.C., III, and Valley, J.W., 1992, Geology and geochemistry of volcanogenic massive sulfide deposits and related igneous rocks, Prince William Sound, south-central Alaska: ECONOMIC GEOLOGY, v. 87, p. 1722–1746.

Dawson, K.M., Panteleyev, A., Sutherland-Brown, A.S., and Woodsworth, G.J., 1992, Regional metallogeny: Boulder, Colorado, Geological Society of America, Geology of North America, v. G2, p. 707–768.

Decker, J., Bergman, S.C., Blodgett, R.B., Box, S.E., Bundtzen, T.K., Clough, J.G., Coonrad, W.L., Gilbert, W.G., Miller, M.F., Murphy, J.M., Robinson, M.S., and Wallace, W.K., 1994, Geology of southwestern Alaska: Boulder, Colorado, Geological Society of America, Geology of North America, v. G1, p. 285–310.

Dickinson, K.A., Cunningham, K.D., and Ager, T.A., 1987, Geology and origin of the Death Valley uranium deposit, Seward Peninsula, Alaska: ECONOMIC GEOLOGY, v. 82, p. 1558–1574.

Dillon, J.T., 1989, Structure and stratigraphy of the southern Brooks Range and northern Koyukuk basin near the Dalton highway: Alaska Division of Geological and Geophysical Surveys Guidebook 7, p. 157–187.

Dillon, J.T., Pessel, G.H., Chen, J.A., and Veach, N.C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, p. 338–343.

Dillon, J.T., Tilton, G.R., Decker, J., and Kelly, M.J., 1987, Resource implications of magmatic and metamorphic ages for Devonian igneous rocks in the Brooks Range, *in* Tailleur, I.L., and Weimer, P., eds., Alaskan North Slope geology: Bakersfield, California, Society of Economic Paleontologists and Mineralogists, Pacific Section, Special Publication 50, p. 713–723.

Duke, N.A., Nauman, C.R., and Newkirk, S.R., 1984, The Delta district, a mineralized lower Paleozoic marginal rift terrane in the east central Alaska Range [abs.]: Geological Society of America Abstracts with Programs, v. 15, p. 279.

Dusel-Bacon, C., 1991, Metamorphic history of Alaska: U.S. Geological Survey Open-File Report 91–556, 48 p.

Duttweiler, K.A., 1987, Use of factor analysis in locating base metal mineralization in the Killik River quadrangle, Alaska: U.S. Geological Survey Circular 998, p. 27–30.

Einaudi, M.T., and Hitzman, M.W., 1986, Mineral deposits in northern Alaska: Introduction: ECONOMIC GEOLOGY, v. 81, p. 1583–1591.

Ellersieck, I.F., Jansons, U., Mayfield, C.F., and Tailleur, I.L., 1982, The Story Creek and Whoopee Creek lead-zinc-silver occurrences, western Brooks Range, Alaska: U.S. Geological Survey Circular 844, p. 35–37.

Foley, J.Y., 1992, Ophiolitic and other mafic-ultramafic metallogenic provinces in Alaska (west of the 141st meridian): U.S. Geological Survey Open-File Report 92–20B, 55 p.

Foley, J.Y., and Barker, J.C., 1985, Chromite deposits along the Border Ranges fault, southern Alaska: U.S. Bureau of Mines Information Circular IC-8990, 58 p.

Foley, J.Y., Barker, J.C., and Brown, L.L., 1985, Critical and strategic minerals in Alaska: Chromite: U.S. Bureau of Mines Open-File Report 97–85, 54 p.

Foley, J.Y., Light, T.D., Nelson, S.W., and Harris, R.A., 1997, Mineral occurrences associated with mafic-ultramafic and related alkaline complexes in Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 396–449.

Folger, P.F., and Schmidt, J.M., 1986, Geology of the carbonate-hosted Omar copper prospect, Baird Mountains, Alaska: ECONOMIC GEOLOGY, v. 81, p. 1690–1695.

Ford, R.C., 1993, Geology, geochemistry, and age of gold lodes at Bluff and Mount Distin, Seward Peninsula, Alaska: Unpublished Ph.D. dissertation, Golden, Colorado, Colorado School of Mines, 302 p.

Ford, R.C., and Snee, L.W., 1996, $^{40}Ar/^{39}Ar$ thermochronology of white mica from the Nome district, Alaska: The first ages of lode sources to placer gold deposits in the Seward Peninsula: ECONOMIC GEOLOGY, v. 91, p. 213–220.

Forrest, K., 1983, Geologic and isotopic studies of the Lik deposit and the surrounding mineral district, Delong Mountains, western Brooks Range, Alaska: Unpublished Ph.D. dissertation, Minneapolis, Minnesota, University of Minnesota, 161 p.

Foster, H.L., Keith, T.E.C., and Menzie, W.D., 1987, Geology of east-central Alaska: U.S. Geological Survey Open-File Report 87–188, 59 p.

Gamble, B.M., and Till, A.B., 1993, Maps showing metallic mineral resources of the Bendeleben and Solomon quadrangles, western Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1838-D, scale 1:250,000.

Gehrels, G.E., and Saleeby, J.B., 1987, Geologic framework, tectonic evolution, and displacement history of the Alexander terrane: Tectonics, v. 6, p. 151–173.

Gehrels, G.E., McClelland, W.C., Samson, S.D., Patchett, P.J., and Orchard, M.J., 1992, Geology of the western flank of the Coast Mountains between Cape Fanshaw and Taku Inlet, southeastern Alaska: Tectonics, v. 11, p. 567–585.

Gillerman, V.S., Brewer, N.H, Millholland, M.A., and Wyman, W.F., 1986, Oxidized polymetallic gold mineralization, Illinois Creek, Alaska, *in* MacDonald, A.J., ed., Gold '86: Poster volume: Toronto, Ontario, Geologic Association of Canada Mineral Deposits Division, p. 51–53.

Goldfarb, R.J., Nelson, S.W., Berg, H.C., and Light, T.D., 1987, Distribution of mineral deposits in the Pacific Border Ranges and Coast Mountains of the Alaskan cordillera, *in* Elliot, I.L., and Smee, B.W., eds., Geoexo/86: Exploration in the North American cordillera: Rexdale, Ontario, Association of Exploration Geochemists, p. 19–41.

Goldfarb, R.J., Gray, J.E., Pickthorn, W.J., Gent, C.A., and Cieutat, B.A., 1990, Stable isotope systematics of epithermal mercury-antimony mineralization, southwestern Alaska: U.S. Geological Survey Bulletin 1950, p. E1–E9.

Goldfarb, R.J., Snee, L.W., Miller, L.D., and Newberry, R.J., 1991, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: Nature, v. 354, p. 296–298.

Goldfarb, R.J., Snee, L.W., and Pickthorn, W.J., 1993, Orogenesis, high-T thermal events, and gold vein formation within metamorphic rocks of the Alaskan cordillera: Mineralogical Magazine, v. 57, p. 375–394.

Goldfarb, R.J., Miller, L.D., Leach, D.L., and Snee, L.W., 1997, Gold deposits in metamorphic rocks of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 151–190.

Gottschalk, R.R., and Snee, L.W., in press, Tectonothermal evolution of metamorphic rocks in the south-central Brooks Range, Alaska: Constraints from $^{40}Ar/^{39}Ar$ geochronology: Geological Society of America Memoir.

Grantz, A., 1956, Magnetite Island deposit at Tuxedni Bay, Alaska: U.S. Geological Survey Bulletin 1024-D, p. 95–106.

Gray, J.E., Goldfarb, R.J., Snee, L.W., and Gent, C.A., 1992, Geochemical and temporal conditions for the formation of mercury-antimony deposits, southwestern Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 24, p. 28.

Gray, J.E., Gent, C.A., Snee, L.W., and Wilson, F.H., 1997, Epithermal mercury-antimony and gold-bearing vein lodes of southwestern Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 287–305.

Haeussler, P.J., Coe, R.S., Robert, S., and Onstott, T.C., 1992, Paleomagnetism of the Late Triassic Hound Island volcanics revisited: Journal of Geophysical Research, v. 97, p. 19617–19639.

Hawley, C.C., and Clark, A.L., 1974, Geology and mineral deposits of the upper Chulitna district, Alaska: U.S. Geological Survey Professional Paper 758-B, 47 p.

Herreid, G., 1970, Geology of the Sirit Mountain nickel-copper prospect and surrounding area: Alaska Division of Mines and Geology Geologic Report 40, 19 p.

Himmelberg, G.R., Loney, R.A., and Nabelek, P.I., 1987, Petrogenesis of gabbronorite at Yakobi and northwest Chichagof Island, Alaska: Geological Society of America Bulletin, v. 98, p. 265–279.

Hitzman, M.W., 1986, Geology of the Ruby Creek copper deposit, southwestern Brooks Range, Alaska: ECONOMIC GEOLOGY, v. 81, p. 1644–1674.

Hitzman, M.W., Proffett, J.M., Jr., Schmidt, J.M., and Smith, T.E., 1986, Geology and mineralization of the Ambler District, northwestern Alaska: ECONOMIC GEOLOGY, v. 81, p. 1592–1618.

Hollister, V.F., 1978, Geology of the porphyry copper deposits of the Western Hemisphere: New York, Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., 219 p.

Hollister, V.F., Anzalone, S.A., and Richter, D.H., 1975, Porphyry copper deposits of southern Alaska and contiguous Yukon Territory: Canadian Mining and Metallurgy Bulletin, v. 68, no. 756, p. 104–112.

Hoy, T., 1991, Volcanogenic massive sulphide deposits in British Columbia: Province of British Columbia Paper 1991–4, p. 89–123.

Hudson, T., 1979, Calc-alkaline plutonism along the Pacific rim of southern Alaska: U.S. Geological Survey Open-File Report 79–953, 31 p.

Hudson, T., and Arth, J.G., 1983, Tin granites of the Seward Peninsula, Alaska: Geological Society of America Bulletin, v. 94, p. 768–790.

Hudson, T., and Plafker, G., 1981, Emplacement age of the Crillon-La Perouse pluton, Fairweather Range: U.S. Geological Survey Circular 823-B, p. B90–B94.

Hudson, T., and Reed, B.L., 1997, Tin deposits in Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 450–465.

Hudson, T., Smith, J.G., and Elliot, R.L., 1979, Petrology, composition, and age of intrusive rocks associated with the Quartz Hill molybdenum deposit, southeastern Alaska: Canadian Journal of Earth Sciences, v. 16, p. 1805–1822.

Hudson, T.L., Arth, J.G., and Muth, K.G., 1981, Geochemistry of intrusive rocks associated with molybdenite deposits, Ketchikan Quadrangle, southeastern Alaska: ECONOMIC GEOLOGY, v. 77, p. 1225–1232.

Irvine, T.N., 1974, Petrology of the Duke Island ultramafic complex, southeastern Alaska: Geological Society of America Memoir 138, 240 p.

Johnston, S.T., and Mortensen, J.K., 1994, Regional setting of porphyry Cu-Mo deposits, volcanogenic massive-sulfide deposits, and mesothermal gold deposits in the Yukon-Tanana terrane, Yukon: Canadian Institute of Mining District 6 Annual General Meeting, 1994, Abstracts and Proceedings, p. 30–34.

Jones, D.L., Silberling, N.J., Gilbert, W., and Coney, P., 1982, Character, distribution, and tectonic significance of accretionary terranes in the central Alaska Range: Journal of Geophysical Research, v. 87, p. 3709–3717.

Jones, D.L., Silberling, N.J., Coney, P.J., and Plafker, G., 1987, Lithotectonic terrane map of Alaska (west of the 141st meridian): U.S. Geological Survey Miscellaneous Field Studies Map MF-1874-A, scale 1:2,500,000.

Kelley, J.S., Tailleur, I.L., Morin, R.L., Reed, K.M., Harris, A.G., Schmidt, J.M., Brown, F.M., and Kurtak, J.M., 1993, Barite deposits in the Howard pass quadrangle and possible relations to barite elsewhere in the northwestern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 93–215, 13 p.

Kennedy, G.C., 1953, Geology and mineral deposits of Jumbo basin, southeastern Alaska: U.S. Geological Survey Professional Paper 251, 46 p.

Kulas, J., 1996, Red Dog's Aqqaluk (Red Dog extension) deposit: World-class zinc discovery in northwest Alaska [abs.]: British Columbia and Yukon Chamber of Mines, 1996 Cordilleran Roundup Abstracts, p. 3–4

Lange, I.M., Nokleberg, W.J., Newkirk, S.R., Aleinikoff, J.N., Church, S.E., and Krouse, H.R., 1993, Devonian volcanogenic massive sulfide deposits and occurrences, southern Yukon-Tanana terrane, eastern Alaska Range, Alaska: ECONOMIC GEOLOGY, v. 88, p. 344–376.

Lanphere, M.A., and Reed, B.L., 1985, The McKinley sequence of granitic rocks: A key element in the accretionary history of southern Alaska: Journal of Geophysical Research, v. 90, p. 11213–11430.

Loney, R.A., and Himmelberg, G.R., 1992, Petrogenesis of the Pd-rich intrusion at Salt Chuck, Prince of Wales Island: An early Paleozoic Alaskan-type ultramafic body: Canadian Mineralogist, v. 30, p. 1005–1022.

Loney, R.A., Brew, D.A., Muffler, L.J.P., and Pomeroy, J.S., 1975, Reconnaissance geology of Chichagof, Baranof, and Kruzof Islands, southeastern Alaska: U.S. Geological Survey Professional Paper 792, 105 p.

Lydon, J.W., 1988, Volcanogenic massive sulfide deposits, 2. Genetic models, *in* Roberts, R.G., and Sheahan, P.A., eds., Ore deposit models: St. John's, Newfoundland, Geological Association of Canada, v. 3, p. 155–181.

MacIntyre, D.G., 1991, Sedex: Sedimentary-exhalative deposits: Province of British Columbia Paper 1991–4, p. 25–70.

MacKevett, E.M., Jr., 1976, Mineral deposits and occurrences in the McCarthy quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-773-B, scale 1:250,000.

MacKevett, E.M., Jr., Cox, D.P., Potter, R.W., III, and Silberman, M.L., 1997, Kennecott-type deposits in the Wrangell Mountains, Alaska: High-grade copper ores near a basalt-limestone contact: ECONOMIC GEOLOGY MONOGRAPH 9, p. 66–89.

Mayfield, C.F., Curtis, S.M., Ellersieck, I.F., and Tailleur, I.L., 1979, Reconnaissance geology of the Ginny Creek Zn-Pb-Ag and Nimiuktuk barite deposits, northwestern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 79–1092, 19 p.

McClelland, W.C., and Gehrels, G.E., 1992, Upper Jurassic-Lower Cretaceous basinal strata along the Cordilleran margin: Implications for the accretionary history of the Alexander-Wrangellia-Peninsular terrane: Tectonics, v. 11, p. 823–835.

McClelland, W.C., Gehrels, G.E., Samson, S.D., and Patchett, P.J., 1992, Structural and geochronological relations along the western flank of the Coast Mountains batholith: Stikine River to Cape Fanshaw, central southeastern Alaska: Journal of Structural Geology, v. 14, p. 475–489.

McCoy, D., Layer, P.W., Newberry, R.J., Bakke, A., Masterman, J.S., and Goldfarb, R.J., 1994, Timing and source of lode gold in the Fairbanks district, interior Alaska [abs.]: U.S. Geological Survey Circular 1107, p. 210.

McCoy, D., Newberry, R.J., Layer, P., DiMarchi, J.J., Bakke, A., Masterman, J.S., and Minehand, D.L., 1997, Plutonic-related gold deposits of interior Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 191–241.

Mertie, J.B., 1976, Platinum deposits of the Goodnews Bay district, Alaska: U.S. Geological Survey Professional Paper 938, 42 p.

Miller, E.L., and Hudson, T.L., 1991, Mid-Cretaceous extensional fragmentation of a Jurassic-Early Cretaceous compressional orogen, Alaska: Tectonics, v. 10, p. 781–796.

Miller, L.D., Goldfarb, R.J., Gehrels, G.E., and Snee, L.W., 1994, Genetic links among fluid cycling, vein formation, regional deformation, and plutonism in the Juneau gold belt, southeastern Alaska: Geology, v. 22, p. 203–206.

Miller, T.P., 1976, Hardrock uranium potential in Alaska: U.S. Geological Survey Open-File Report 76–246, 7 p.

——1989, Contrasting plutonic rock suites of the Yukon-Koyukuk basin and the Ruby geanticline, Alaska: Journal of Geophysical Research, v. 94, p. 15969–15987.

Miller, T.P., and Bunker, C.M., 1976, A reconnaissance study of the uranium and thorium contents of plutonic rocks of the southeastern Seward Peninsula, Alaska: U.S. Geological Survey Journal of Research, v. 4, p. 367–377.

Moffit, F.H., and Mertie, J.B., Jr., 1923, The Kotsina-Kuskalana district, Alaska: U.S. Geological Survey Bulletin 745, 149 p.

Moll-Stalcup, E.J., 1994, Latest Cretaceous and Cenozoic magmatism in mainland Alaska, *in* Plafker, G., and Berg, H.C., eds., The geology of Alaska: Boulder, Colorado, Geological Society of America, v. G1, p. 589–619.

Monger, J.W.H., and Berg, H.C., 1987, Lithotectonic terrane map of western Canada and southeastern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1874-B, 12 p., scale 1:2,500,000.

Moore, D.W., Young, L.E., Modene, J.S., and Plahuta, J.T., 1986, Geologic setting and genesis of the Red Dog zinc-lead-silver deposit, western Brooks Range, Alaska: ECONOMIC GEOLOGY, v. 81, p. 1696–1727.

Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Geology of northern Alaska: Boulder, Colorado, Geological Society of America, Geology of North America, v. G1, p. 49–140.

Mortensen, J.K., 1992, Pre-mid-Mesozoic tectonic evolution of the Yukon-Tanana terrane, Yukon and Alaska: Tectonics, v. 11, p. 836–853.

Mull, C.G., 1982, The tectonic evolution and structural style of the Brooks Range, Alaska: An illustrated summary, *in* Powers, R.B., ed., Geological studies of the Cordilleran thrust belt: Denver, Colorado, Rocky Mountain Association of Geologists, v. 1, p. 1–45.

Myers, G.L., 1984, Geology of the Cu-Fe-Au skarns of Kasaan peninsula, southeastern Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 16, p. 327.

——1985, Gold distribution in the Fe-Cu-Au skarns of the Kasaan peninsula, southeast Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 17, p. 397.

Nelson, B.K., Nelson, S.W., and Till, A.B., 1993, Nd- and Sr-isotope evidence for Proterozoic and Paleozoic crustal evolution in the Brooks Range, northern Alaska: Journal of Geology, v. 101, p. 435–450.

Nelson, W.H., Carlson, C., and Case, J.E., 1983, Geologic map of the Lake Clark quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1114-A, scale 1:250,000.

Newberry, R.J., and Brew, D.A., 1988, Epigenetic hydrothermal origin of the Groundhog basin-Glacier basin silver-lead-tin-zin deposits, southeastern Alaska: U.S. Geological Survey Bulletin 1903, p. 113–120.

Newberry, R.J., Burns, L.E., and Pessel, G.H., 1986a, Volcanogenic massive sulfide deposits and the "missing complement" to the calc-alkaline trend: Evidence from the Jurassic Talkeetna island arc of southern Alaska: ECONOMIC GEOLOGY, v. 81, p. 951–960.

Newberry, R.J., Dillon, J.T., and Adams, D.D., 1986b, Regionally metamorphosed, calc-silicate-hosted deposits of the Brooks Range, northern Alaska: ECONOMIC GEOLOGY, v. 81, p. 1728–1752.

Newberry, R.J., Burns, L.E., Swanson, S.E., and Smith, T.E., 1990, Comparative petrologic evolution of the Sn and W granites of the Fairbanks–Circle area, interior Alaska: Geological Society of America Special Paper 246, p. 121–142.

Newberry, R.J., Crafford, T.C., Newkirk, S.R., Young, L.E., Nelson, S.W., and Duke, N.A., 1997a, Volcanogenic massive sulfide deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 120–150.

Newberry, R.J., Allegro, G.L., Cutler, S.E., Hagen-Levelle, J.H., Adams, D.D., Nicholson, L.C., Weglarz, T.B., Bakke, A.A., Clautice, K.H., Coulter, G.A., Ford, M.J., Myers, G.L., and Szumigala, D.J., 1997b, Skarn deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 355–395.

Nokleberg, W.J., and Winkler, G.R., 1982, Stratiform zinc-lead deposits in the Drenchwater Creek area, Howard pass quadrangle, northwestern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 1209, 22 p.

Nokleberg, W.J., Bundtzen, T.K., Berg, H.C., Brew, D.A., Grybeck, D.J., Robinson, M.S., Smith, T.E., and Yeend, W.E., 1987, Significant metalliferous lode deposits and placer districts of Alaska: U.S. Geological Survey Bulletin 1786, 104 p.

Norford, B.S., and Mihalynuk, M.G., 1994, Evidence of the Pacific faunal province in northern Alexander terrane, recognition of two Middle Ordovician graptolite zones in northwestern British Columbia: Canadian Journal of Earth Sciences, v. 31, p. 1384–1396.

Patton, W.W., Jr., 1970, A discussion of tectonic history of northern Alaska [abs.]: American Association of Petroleum Geologists Geological Seminar on the North Slope of Alaska, Pacific Section, Bakersfield, California, Proceedings, p. E20.

Patton, W.W., Jr., and Box, S.E., 1989, Tectonic setting of the Yukon-Koyukuk basin and its borderlands, western Alaska: Journal of Geophysical Research, v. 94, p. 15807–15820.

Pavlis, T.L., Sisson, V.B., Foster, H.L., Nokleberg, W.J., and Plafker, G., 1993, Mid-Cretaceous extensional tectonics of the Yukon-Tanana terrane, trans-Alaska crustal transect (TACT), east-central Alaska: Tectonics, v. 12, p. 103–122.

Philpotts, J.A., Taylor, C.D., Jr., Evans, J., and Emsbo, P., 1993, Newly discovered molybdenite occurrences at Dora Bay, Prince of Wales Island, southeast Alaska, and preliminary scanning electron microscope studies: U.S. Geological Survey Bulletin 2068, p. 187–196.

Plafker, G., and Berg, H.C., 1994, Overview of the geology and tectonic evolution of Alaska: Boulder, Colorado, Geological Society of America, Geology of North America, v. G1, p. 989–1021.

Plafker, G., Blome, C.D., and Silberling, N.J., 1989a, Reinterpretation of lower Mesozoic rocks on the Chilkat peninsula, Alaska, as a displaced fragment of Wrangellia: Geology, v. 17, p. 3–6.

Plafker, G., Nokleberg, W.J., and Lull, J.S., 1989b, Bedrock geology and tectonic evolution of the Wrangellia, Peninsular, and Chugach terranes along the trans-Alaska crustal transect in the northern Chugach Mountains and southern Copper River basin, Alaska: Journal of Geophysical Research, v. 94, p. 4255–4295.

Plafker, G., Moore, J.C., and Winkler, G.R., 1994, Geology of the southern Alaska margin: Boulder, Colorado, Geological Society of America, Geology of North America, v. G1, p. 389–449.

Ray, G.E., and Webster, C.L., 1991, An overview of skarn deposits, *in* McMillan, W.J., Hoy, T., et al., eds., Ore deposits, tectonics, and metallogeny in the Canadian Cordillera: Province of British Columbia Paper 1991–4, p. 213–252.

Reed, B.L., and Eberlein, G.D., 1972, Massive sulfide deposits near Shellebarger pass, southern Alaska Range: U.S. Geological Survey Bulletin 1342, 45 p.

Reed, B.L., and Nelson, S.W., 1977, Geologic map of the Talkeetna quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-870-A, scale 1:250,000.

Reed, B.L., Nelson, S.W., Curtin, G.C., and Singer, D.A., 1978, Mineral resource map of the Talkeetna quadrangle: U.S. Geological Survey Miscellaneous Field Studies Map MF-870-D, scale 1:250,000.

Reed, B.L., Miesch, A.T., and Lanphere, M.A., 1983, Plutonic rocks of Jurassic age in the Alaska-Aleutian Range batholith: Chemical variations and polarity: Geological Society of America Bulletin, v. 94, p. 1232–1240.

Richter, D.H., and Herreid, G., 1965, Geology of the Paint River area, Iliamna quadrangle, Alaska: Alaska Division of Mines and Minerals Geologic Report 8, 8 p.

Richter, D.H., Singer, D.A., and Cox, D.P., 1975, Mineral resources map of the Nabesna quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-655-K, scale 1:250,000.

Rockingham, C., 1993, Johnson River: Alaska's Jurassic Park [abs.]: Alaska Miners Association Annual Convention, Anchorage, Alaska, November 1–5, 1993, Abstracts and Papers, p. 2.

Roeske, S.M., Pavlis, T.L., Snee, L.W., and Sisson, V.B., 1991, $^{40}Ar/^{39}Ar$ isotopic ages from the combined Wrangellia-Alexander terrane along the Border Ranges fault system in the eastern Chugach Mountains and Glacier Bay, Alaska: U.S. Geological Survey Bulletin 1999, p. 180–195.

Rubin, C.M., and Saleeby, J.B., 1992, Tectonic history of the eastern edge of the Alexander terrane, southeast Alaska: Tectonics, v. 11, p. 586–602.

Rubin, C.M., Miller, M.M., and Smith, G.M., 1990, Tectonic setting of Cordilleran mid-Paleozoic volcano-plutonic complexes: Evidence for convergent margin tectonism: Geological Society of America Special Paper 255, p. 1–16.

Sainsbury, C.L., 1988, Vertical and horizontal zoning from tin to beryllium deposits, Lost River district, Alaska: North American Conference on Tectonic Control of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems, Rolla, Missouri, 1988, Proceedings, p. 80–91.

Saleeby, J.B., 1992, Age and tectonic setting of the Duke Island ultramafic intrusion, southeast Alaska: Canadian Journal of Earth Sciences, v. 29, p. 506–522.

Samson, S.D., Patchett, P.J., Gehrels, G.E., and Anderson, R.G., 1990, Nd and Sr isotopic characterization of the Wrangellia terrane and implications for crustal growth of the Canadian Cordillera: Journal of Geology, v. 98, p. 749–762.

Schmidt, J.M., 1997a, Shale-hosted Zn-Pb-Ag and barite deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 35–65.

——1997b, Strata-bound carbonate-hosted Zn-Pb and Cu deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 90–119.

Schmidt, J.M., and Werdon, M.B., 1993, Clastic-hosted stratiform, vein/breccia and disseminated Zn-Pb-Ag deposits of the northwestern Brooks Range, Alaska: Are they different expressions of dewatering of the same source basin? [abs.]: Geological Society of America Abstracts with Programs, v. 25, p. 143.

Schmidt, J.M., and Zierenberg, R.A., 1987, The Red Dog Pb-Zn-Ag deposit, Alaska: An example of nonexhalative processes in the formation of syngenetic massive sulfides [abs.]: U.S. Geological Survey Circular 995, p. 61.

Silberman, M.L., Matthews, A., Potter, R.W., and Nissenbaum, A., 1978, Stable isotope geochemistry, sulfide mineralogy, and potassium-argon ages of the Kennecott massive sulfide deposits, Alaska: U.S. Geological Survey Circular 772-B, p. B56–B58.

Sinclair, W.D., 1986, Molybdenum, tungsten, and tin deposits and associated granitoid intrusions in the northern Canadian Cordillera and adjacent parts of Alaska: Canadian Institute of Mining and Metallurgy Special Volume 37, p. 216–233.

Smith, T.E., 1981, Geology of the Clearwater Mountains, south-central Alaska: Alaska Division of Geological and Geophysical Surveys Report 60, 72 p.

Smith, T.E., Albanese, M.D., and Kline, G.L., 1988, Geologic map of the Healy A-2 quadrangle, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 84–14, scale 1:63,360.

Steefel, C.I., 1987, The Johnson River prospect, Alaska: Gold-rich sea-floor mineralization from the Jurassic: ECONOMIC GEOLOGY, v. 82, p. 894–914.

Stevens, D.L., 1971, Geology and geochemistry of the Denali prospect, Clearwater Mountains, Alaska: Unpublished Ph.D. dissertation, Fairbanks, Alaska, University of Alaska, 81 p.

Still, J.C., 1984, Copper, gold, platinum, and palladium sample results from the Klukwan mafic/ultramafic complex, southeast Alaska: U.S. Bureau of Mines Open-File Report 84–21, 16 p.

Swainbank, R.C., Smith, T.E., and Turner, D.L., 1977, Geology and K-Ar ages of mineralized intrusive rocks from the Chulitna mining district, central Alaska: Alaska Division of Geological and Geophysical Surveys Geologic Report 55, p. 23–28.

Swanson, S.E., Newberry, R.J., Coulter, G.A., and Dyhouse, T.M., 1990, Mineralogical variation as a guide to the petrogenesis of the tin granites and related skarns, Seward Peninsula, Alaska: Geological Society of America Special Paper 246, p. 143–160.

Szumigala, D.J., 1985, Geology of the Tin Creek zinc-lead skarn deposits, McGrath B-2 quadrangle, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 85–50, 10 p.

——1986, Geology and geochemistry of the Tin Creek skarn prospects, Farewell mining district, southwestern Alaska: Unpublished M.S. thesis, Fairbanks, Alaska, University of Alaska, 144 p.

——1993, Gold mineralization related to Cretaceous-Tertiary magmatism in the Kuskokwim Mountains of west-central and southwestern Alaska: Unpublished Ph.D. dissertation, Los Angeles, California, University of California, 301 p.

Tailleur, I.L., 1980, Rationalization of Koyukuk "crunch," northern and central Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 64, p. 792.

Taylor, C.D., Goldfarb, R.J., Snee, L.W., Gent, C.A., Karl, S.M., and Haeussler, P.J., 1994, New age data for gold deposits and granites, Chichagof mining district, SE Alaska: Evidence for a common origin [abs.]: Geological Society of America Abstracts with Programs, v. 26, p. A140.

Taylor, C.D., Philpotts, J.A., Sutley, S.J., Gent, C.A., Harlan, S.S., Premo, W.R., Tatsumoto, M., Emsbo, P., and Meier, A.L., 1995, Geochemistry of Late Triassic volcanic host rocks and age of alteration associated with volcanogenic massive sulfide occurrences, Alexander terrane, southeast Alaska [abs.]: Geology and Ore Deposits of the American Cordillera, Reno/Sparks, Nevada, 1995, Program with Abstracts, p. A74.

Taylor, H.P., Jr., and Noble, J.A., 1969, Origin of magnetite in the zoned ultramafic complexes of southeastern Alaska: ECONOMIC GEOLOGY MONOGRAPH 4, p. 209–230.

Theodore, T.G., and Menzie, W.D., 1984, Fluorine-deficient porphyry molybdenum deposits in the western North America cordillera: International Association on the Genesis of Ore Deposits (IAGOD), 6th, Proceedings, p. 463–470.

Thompson, T.B., 1997, Uranium, thorium, and rare metal deposits of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 466–482.

Till, A.B., and Dumoulin, J.A., 1994, Geology of Seward Peninsula and Saint Lawrence Island, *in* Plafker, G., and Berg, H.C., eds., The geology of Alaska: Boulder, Colorado, Geological Society of America, v. G1, p. 141–152.

Till, A.B., Box, S.E., Roeske, S.M., and Patton, W.W., Jr., 1993, Comment on "Mid-Cretaceous extensional fragmentation of a Jurassic-Early Cretaceous compressional orogen, Alaska," by E.L. Miller and T.L. Hudson: Tectonics, v. 12, p. 1076–1081.

Twenhofel, W.S., Reed, J.C., and Gates, G.O., 1949, Some mineral investigations in southeastern Alaska: U.S. Geological Survey Bulletin 963-A, p. 1–45.

U.S. Geological Survey and U.S. Bureau of Mines, 1984, Mineral resources of the Tracy Arm-Fords Terror Wilderness study area and vicinity, Alaska: U.S. Geological Survey Bulletin 1525, 308 p.

Wallace, W.K., Hanks, C.L., and Rogers, J.F., 1989, The southern Kahiltna terrane: Implications for the tectonic evolution of southwestern Alaska: Geological Society of America Bulletin, v. 101, p. 1389–1407.

Warner, J.D., 1985, Critical and strategic minerals in Alaska: Tin, tantalum, and columbium: U.S. Bureau of Mines Information Circular 9037, 42 p.

Warner, L.A., Goddard, E.N., and others, 1961, Iron and copper deposits of the Kasaan peninsula, Prince of Wales Island, southeastern Alaska: U.S. Geological Survey Bulletin 1090, 136 p.

Wayland, R.G., 1943, Gold deposits near Nabesna: U.S. Geological Survey Bulletin 933-B, p. 175–199.

Werdon, M.B., 1995, Drenchwater, Alaska: Sedimentary exhalative deposit, volcanogenic massive sulfide deposit, or both? [abs.]: Geology and Ore Deposits of the American Cordillera, Reno/Sparks, Nevada, 1995, Program with Abstracts, p. A78.

White, W.H., Bookstrom, A.A., Kamilli, A.A., Ganster, M. W., Smith, R.P., Ranta, D.E., and Steininger, R.C., 1981, Character and origin of Climax-type molybdenum deposits: ECONOMIC GEOLOGY 75TH ANNIVERSARY VOLUME, p. 270–316.

Wilson, F.H., 1985, The Meshik arc: An Eocene to earliest Miocene magmatic arc on the Alaska Peninsula: Alaska Division of Geological and Geophysical Surveys Professional Report 88, 14 p.

Wilson, F.H., and Cox, D.P., 1983, Geochronology, geochemistry, and tectonic environment of porphyry mineralization in the central Alaska Peninsula: U.S. Geological Survey Open-File Report 83–783, 24 p.

Wilson, F.H., Shew, N.B., DuBois, G.D., and Bie, S.W., 1994, Sample locality map and analytical data for potassium-argon ages in the Port Moller, Stepovak Bay, and Simeonof Island quadrangles, Alaska Peninsula: U.S. Geological Survey Miscellaneous Field Studies Map MF-2155-E, scale 1:250,000.

Wilson, F.H., White, W.H., Detterman, R.L., and Case, J.E., 1995, Maps showing the resource assessment of the Port Moller, Stepovak Bay, and Simeonof quadrangles, Alaska Peninsula: U.S. Geological Survey Miscellaneous Field Studies Map MF-2155-F, scale 1:250,000.

Winkler, G.R., 1992, Geologic map and summary geochronology of the Anchorage 1° × 3° quadrangle, southern Alaska: U.S. Geological Survey Miscellaneous Geological Investigations Map I-2283, scale 1:250,000.

Wirth, K.R., and Bird, J.M., 1992, Chronology of ophiolite crystallization, detachment, and emplacement: Evidence from the Brooks Range, Alaska: Geology, v. 20, p. 75–78.

Woodsworth, G.J., Anderson, R.G., and Armstrong, R.L., 1991, Plutonic regimes, *in* Gabrielse, H., and Yorath, C.J., eds., Geology of the Cordilleran orogen in Canada: Canada Geological Survey, Geology of Canada, no. 4, p. 491–531.

Young, L.E., 1989, Geology and genesis of the Red Dog deposit, western Brooks Range, Alaska: Canadian Mining and Metallurgy Bulletin, v. 82, no. 929, p. 57–67.

Young, L.E., St. George, P., and Bouley, B.A., 1997, Porphyry copper deposits in relation to the magmatic history and palinspastic restoration of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 306–333.