Orogenesis, high-*T* thermal events, and gold vein formation within metamorphic rocks of the Alaskan Cordillera

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Abstract

Mesothermal, gold-bearing quartz veins are widespread within allochthonous terranes of Alaska that are composed dominantly of greenschist-facies metasedimentary rocks. The most productive lode deposits are concentrated in south-central and southeastern Alaska; small and generally nonproductive gold-bearing veins occur upstream from major placer deposits in interior and northern Alaska. Ore-forming fluids in all areas are consistent with derivation from metamorphic devolatilisation reactions, and a close temporal relationship exists between high-*T* tectonic deformation, igneous activity, and gold mineralization. Ore fluids were of consistently low salinity, CO_2-rich, and had $\delta^{18}O$ values of 7‰–12‰ and δD values between −15‰ and −35‰. Upper-crustal temperatures within the metamorphosed terranes reached at least 450–500 °C before onset of significant gold-forming hydrothermal activity. Within interior and northern Alaska, latest Paleozoic through Early Cretaceous contractional deformation was characterised by obduction of oceanic crust, low-*T*/high-*P* metamorphism, and a lack of gold vein formation. Mid-Cretaceous veining occurred some 50–100 m.y. later, during a subsequent high-*T* metamorphic/magmatic event, possibly related to extension and uplift. In southern Alaska, gold deposits formed during latter stages of Tertiary, subduction-related, collisional orogenesis and were often temporally coeval with calc-alkaline magmatism.

KEYWORDS: mesothermal gold, Alaska, fluid inclusion, stable isotope, geochronology, orogensis.

Introduction

A TOTAL of 32 million ounces of gold has been recovered from placer and lode occurrences throughout Alaska (Cobb, 1984*a*,*b*; Swainbank *et al.*, 1991). Just over 25% of this production has come from Tertiary mesothermal vein deposits along the Pacific rim (Fig. 1). Past lode producers include mines of the Juneau gold belt and Chichagof district in southeastern Alaska, and mines of the Willow Creek district and Chugach/Kenai Mountains in south-central Alaska (Table 1). In addition, present estimates of ore reserves within the Juneau gold belt exceed the 6.8 million ounces of past gold production. With the exception of a shallow epithermal system (the Apollo mine) on the Alaska Peninsula in southwest Alaska, the State's major lode deposits show remarkable similarities in metamorphic setting, associated magmatism, and geochemical characteristics. Lode development in southern and southeastern Alaska is inherently related to processes accompanying convergence and orogenesis within the accretionary terranes of the northern Pacific Ocean basin.

The majority of Alaska's gold, however, has been recovered from Nome, Fairbanks, and other interior Alaska placer accumulations (Fig. 2). Gold was originally deposited in quartz veins during the Cretaceous, and these lodes eroded to form productive placers during subsequent uplift. The Mesozoic transpressional and subsequent extensional tectonic evolution of interior Alaska is still poorly understood and extremely controversial. However, studies of the generally subeconomic, small, auriferous quartz lodes remain-

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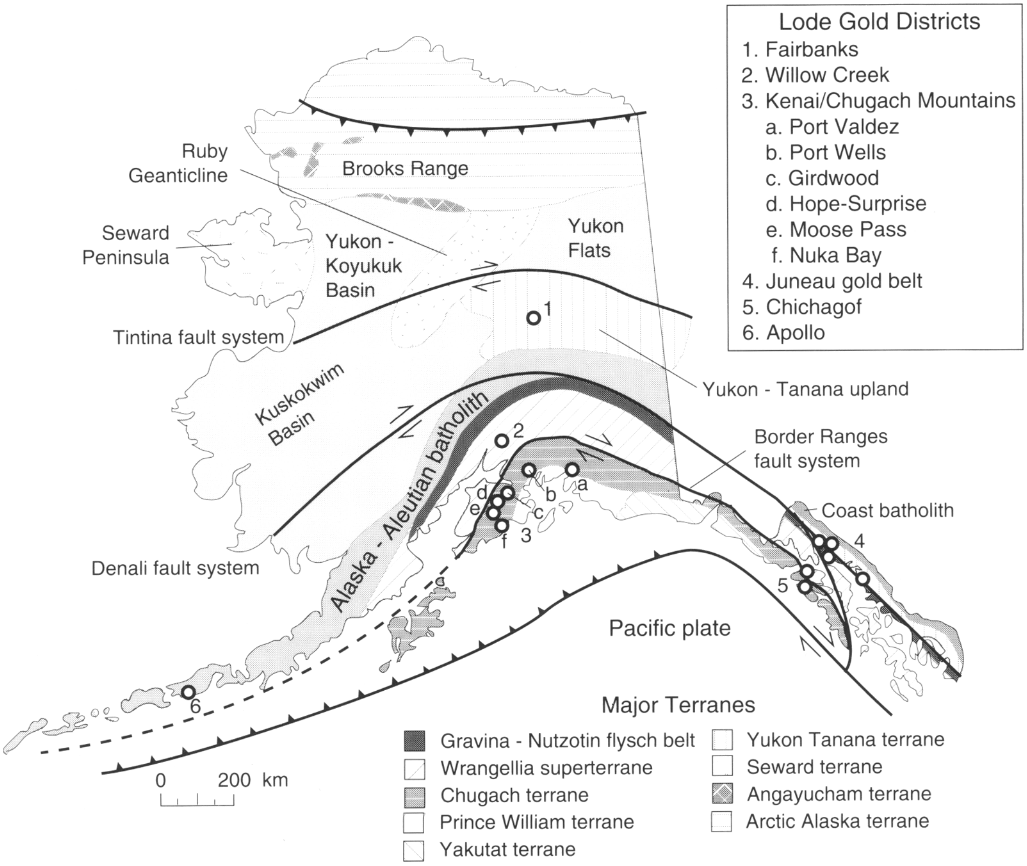


FIG. 1. Distribution of important lode gold deposits in Alaska.

ing upstream of the placer deposits suggest that many placers in central and northern Alaska were derived from veins that formed under similar P–T–X conditions to those located along the southern Alaskan margin. The scarcity of economic mesothermal lodes in interior Alaska reflects the relatively short lifetime (<100 m.y.) from formation to erosion of mesothermal vein deposits in environments of relatively long-lived (many tens of millions of years) tectonism.

This paper summarises many features common to most gold districts within Alaska. Metamorphic setting, close temporal relationships with magmatism, and fluid inclusion and stable isotope geochemistry of the ore fluids from many of the deposits are notably consistent. Emplacement of gold-bearing veins consistently post-dates metamorphism of immediate vein host rocks. Pyrite and arsenopyrite, with lesser galena, sphalerite, chalcopyrite, pyrrhotite, and (or) stibnite, are the common sulphide phases. Carbonate minerals and hydrothermal micas are generally the most abundant gangue phases, especially in vein systems cutting igneous country rocks. Most veins are hosted by greenschist-facies metamorphic rocks within accreted terranes, show evidence of both brittle and ductile deformation, and are spatially associated with major crustal structures. These observations indicate some inherent similarities for hydrothermal ore formation in the northern Cordillera of North America. But, whereas geological and geochemical characteristics indicate a common fluid type, absolute and relative ages of vein formation show that hydrothermal mineralisation is a product of different tectonic regimes. The significant lode deposits of southern Alaska developed towards the end of a long period of contractional orogenesis within areas of either orthogonal or oblique convergence. However, the source lodes for major, interior Alaska gold placers apparently formed during a widespread, crustal, high-temperature episode, perhaps driven by a major extensional event (Pavlis, 1989; Miller and Hudson, 1991),

Table 1. Alaskan gold production through 1992. Total production is about 32 million ounces, 27 percent of which was from lode sources.

LODE GOLD	Gold (oz)
Juneau	6,800,000
Chichagof	770,000
Willow Creek	624,000
Fairbanks	285,000
Chugach/Kenai Mountains	132,000
Apollo	108,000
PLACER GOLD	
Fairbanks	8,000,000
Nome	6,000,000
Flat	1,536,000
Circle	918,000
Kuskokwim	600,000
Innoko	582,000
Forty Mile	501,000
Hot Springs	450,000
Tolvana	440,000
Ruby	420,000
Valdez Creek	400,000
Koyukuk	340,000
Nyak	230,000
Chistochina	177,000
Nizina	144,000
Chugach/Kenai Mountains	133,000
Yetna	115,000
Marshall	113,000

which post-dated collision by many tens of millions of years.

Mesozoic to Cenozoic evolution of Alaska

Alaska is composed of more than 50 lithotectonic terranes of predominantly oceanic affinity (Jones *et al.*, 1987; Monger and Berg, 1987). Prior to the Late Jurassic, the area west of the North American craton existed as a passive continental margin. Beginning in the Late Jurassic, and continuing for the next 120 million years, an exceptional period of accretionary continental growth and orogenesis led to the development of the present framework of Alaska (Coney, 1989). This consisted of a complex sequence of terrane accretion, subduction or obduction, deformation, magmatism, metamorphism, strike–slip motion, possible lithospheric delamination with related extension, and, quite commonly, gold-vein formation.

Growth of the northernmost Alaskan Cordillera occurred during a major period of convergent-margin compressional deformation between about 170 ± 10 Ma and 131 Ma (Miller and Hudson, 1991). This included development of the Brooks Range fold and thrust belt, which involved the obduction of sheets of mafic volcanic rocks and associated oceanic sedimentary units of the Angayuchum terrane northward onto sedimentary rocks, largely of shelf-facies affinity, of the Arctic Alaska terrane. The underthrusted rocks along the southern part of the Arctic Alaska terrane underwent regional blueschist-facies metamorphism during the Triassic part of this Brookian orogeny (Till, 1992; Christiansen and Snee, in press) and were largely overprinted by greenschist-facies assemblages during later decompression, (Dusel-Bacon, 1991). The compressional events may have been followed by up to 40 m.y. of solely mid-Cretaceous crustal extensional (Miller and Hudson, 1991) or, synchronously, latest phases of local contraction may have been accompanied by mid-Cretaceous extension (Gottschalk *et al.*, in press) that aided uplift of the Brooks Range. The extent, absolute age, and significance of the extension is currently the subject of debate (Till *et al.*, in press). The lack of Mesozoic magmatic activity across the entire Brooks Range is exceptionally noteworthy.

The Seward Peninsula, immediately southwest of the Brooks Range is largely composed of Precambrian(?) and early Paleozoic schist and marble of the Seward terrane (Till and Dumoulin, in press). Rocks of this shallow-water and shelf-facies sequence were also subjected to compressional tectonism during the Brookian orogeny. Sheets of oceanic rocks of the Angayuchum terrane were probably obducted onto the Seward terrane, resulting in a blueschist-facies metamorphic event similar to that observed in the southern Brooks Range (Till and Dumoulin, in press). Unlike the Brooks Range, however, the Seward Peninsula was subsequently affected by a moderate- to high-T magmatic and metamorphic event in mid-Cretaceous time (Thurston, 1985).

The tectonic development of interior Alaska, south of the Brooks Range–Seward Peninsula and north of the Denali fault system, is poorly understood. The region is largely comprised of the Yukon–Tanana upland to the east, the Ruby Geanticline in the centre, and the Yukon–Koyukuk and Kuskokwim basins to the west. The extensive region between the Tintina and Denali fault systems in easternmost central Alaska and in the adjacent Yukon Territory is underlain by Paleozoic and probable Proterozoic schist, gneiss, and meta-plutonic rocks of the Yukon–Tanana and closely related, smaller terranes (Jones *et al.*, 1987). Southwest-dipping subduction of western

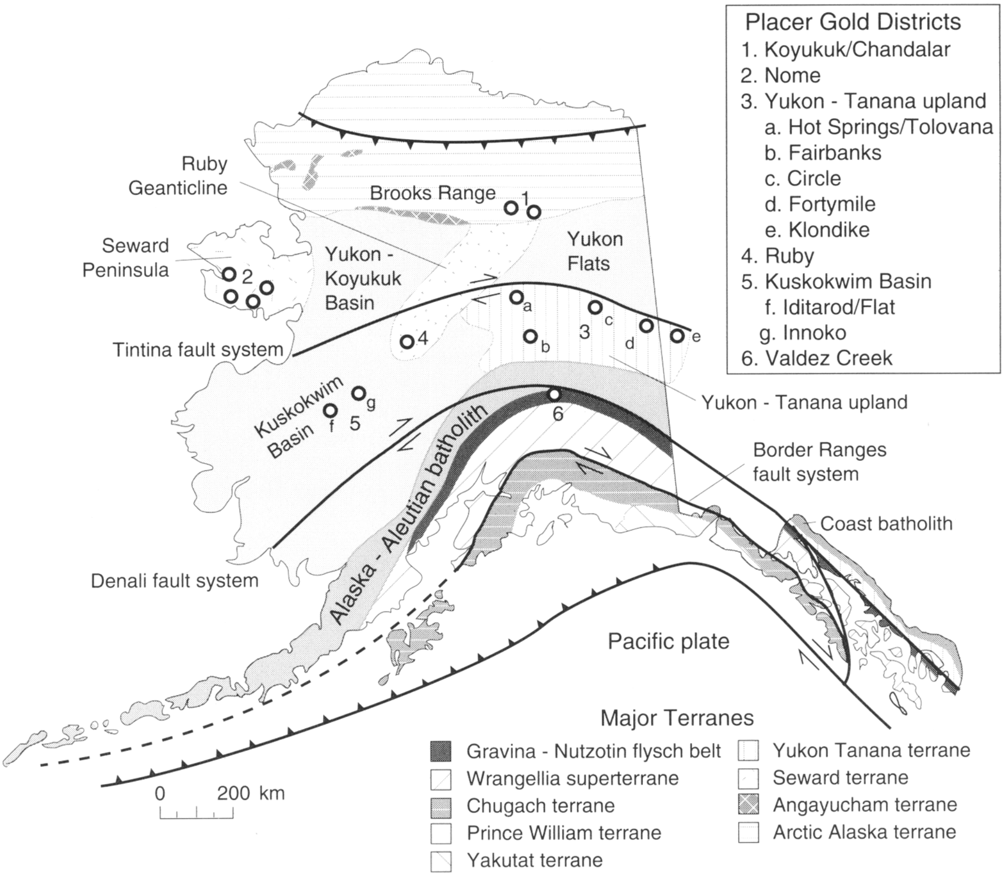


FIG. 2. Distribution of important placer gold deposits in Alaska.

North America below the adjacent ocean basin began at the end of the Permian and continued through the Triassic and Jurassic (Hansen, 1990). This Jurassic compressional event was followed by widespread mid-Cretaceous extension and uplift that is believed to be coeval with a similar event across the southern Brooks Range (Pavlis *et al.*, 1993). The resulting upland, generally termed the Yukon–Tanana terrane, was subjected to widespread magmatic activity between 110–85 Ma and 70–50 Ma (Foster *et al.*, 1987). Whereas contact metamorphism is associated with both periods of magmatism, regional greenschist-facies minerals pre-date Albian time (Dusel-Bacon, 1991). The Ruby Geanticline is a diagonal uplift trending across central Alaska. Like the Seward Peninsula and Yukon–Tanana upland, it consists of predominantly Paleozoic miogeoclinal assemblages that were underthrusted below oceanic rocks in the Late Jurassic and Early Cretaceous, were metamorphosed to blueschist–greenschist facies, and then were uplifted and intruded by mesozonal, granitic plutons in the mid-Cretaceous (Patton and Box, 1989; Roeske *et al.*, in press).

The Yukon–Koyukuk and Kuskokwim basins, covering most of western Alaska, consist of numerous, small, arc and subduction-complex fragments that were amalgamated and linked by Mid- and Late Cretaceous, terrigenous overlap sedimentary deposits. These small terranes and overlapping sedimentary deposits were accreted onto the western margin of North America by latest Cretaceous to early Tertiary time (Wallace *et al.*, 1989). They were intruded by latest Cretaceous to early Eocene and late Eocene through Oligocene granitic rocks. For the most part, these rocks of western Alaska are unmetamorphosed or metamorphosed to very low grades (Dusel-Bacon, 1991).

South of the Denali fault system, Alaska consists of a series of arcuate accreted volcanic and sedimentary oceanic terranes. The Wrangellia superterrane, also known as Composite Terrane II (Monger *et al.*, 1982) or the southern Alaska superterrane (Panuska and Stone, 1985), consists of the distinct Peninsular, Wrangellia, and Alexander terranes. These terranes were amalgamated into a single 'superterrane' prior to mid-Cretaceous accretion to the Yukon-Tanana and to a number of smaller terranes that are exposed along the Denali fault system. Late Jurassic to mid-Cretaceous flysch basin overlap assemblages mark the zone of suturing (Berg *et al.*, 1972; Wallace *et al.*, 1989). Late Jurassic and Cretaceous flysch, melange, and minor mafic volcanic rocks of the Chugach terrane were accreted to and subducted below the southern Alaska superterrane by the latest Cretaceous (Plafker, 1987). Oceanic sedimentary rocks and associated basalts of the Prince William and Yakutat terranes were accreted onto the southern Alaska margin by about 51 Ma and 20 Ma, respectively (op. cit.).

The southern Alaskan terranes characteristically show facies representative of Barrovian metamorphic sequences, with metamorphic grade increasing inboard within each terrane. Regional metamorphism accompanied subduction and deformation. Much of the Wrangellia superterrane and the Chugach terrane are underlain by greenschist- and amphibolite-facies rocks. Exposed parts of the Prince William terrane are generally sub-greenschist facies and similar parts of the Yakutat terrane are unmetamorphosed (Dusel-Bacon, 1991). The Cretaceous to Eocene (72–48 Ma) Coast batholith, the largest continental-margin batholith in the world, occurs inboard of the Jurassic and Cretaceous flysch basin in southeastern Alaska (Barker *et al.*, 1986). Magmatic activity forming the Alaska–Aleutian Range batholith occurred inboard of the flysch sequence in the Alaska Range of south-central Alaska between 74–55 Ma and in the Aleutian arc of southwest Alaska between 42–21 Ma (Reed *et al.*, 1983). The relatively small Talkeetna Mountains batholith intruded rocks of the Peninsular terrane in south-central Alaska in the Late Cretaceous and early Tertiary. A 57–50 Ma and 39–34 Ma suite of plutons in the forearc intrude both the Chugach and Prince William terranes (Hudson and Plafker, 1982).

Alaskan gold districts

Brooks Range, Northern Alaska. Much of northern Alaska, and in particular almost the entire Brooks Range, lacks placer and lode gold deposits. Orogenic belts throughout the world that are dominated by greenschist-facies metamorphic rocks characteristically contain mesothermal gold vein deposits. Therefore, the greenschist-facies sedimentary rocks that comprise much of the southern half of the Brooks Range are anomalous. Understanding why such an extensive belt of greenschist-facies rocks is so gold-poor could be valuable in isolating criteria necessary for mesothermal gold formation; that is, what factors are lacking in the evolution of the Brooks Range that are present in other, gold-rich greenschist belts? The Chandalar–Koyukuk region in the eastern side of the range (Fig. 3) yielded at least 330 000 oz of gold from placer mines (Swainbank *et al.*, 1991) and is the only significant gold district in the Brooks Range; none of the other rare and scattered placer occurrences reported across the southern Brooks Range yielded more than a few tens of thousands ounces of gold.

Small gold- and stibnite-bearing quartz veins are scattered throughout the Chandalar–Koyukuk region. These veins in the eastern Brooks Range occur within high-angle shear zones that clearly developed subsequent to Early Cretaceous upper greenschist-facies metamorphism of the host pelitic sedimentary rocks. Dillon *et al.* (1987) hypothesised that some gold in the Chandalar and Koyukuk districts was originally deposited by magmatic processes in

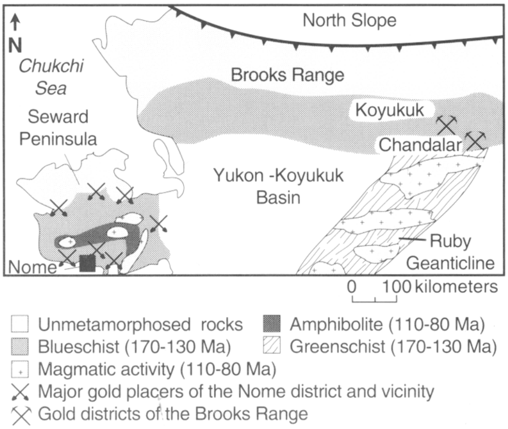


FIG. 3. Gold placers, and associated minor lodes, in northern Alaska are spatially associated with areas affected by Mid- to Late Cretaceous, high-*T* thermal events. The only significant gold accumulations across the 1200 km long Brooks Range are 30–40 km north of voluminous plutonic bodies near the contact with the Ruby Geanticline. Placers of the Nome district surround high-grade metamorphic rocks and anatectic plutons within the core of the Seward Peninsula.

cupolas of Devonian granites because many veins in the districts are spatially associated with adjacent hornfels. They state that, during Albian uplift, the gold was remobilised into host structures by metamorphic fluids migrating up from deeper within the metamorphic pile. Rose *et al.* (1988) interpreted stable isotope and fluid inclusion data from gold-bearing veins as suggestive of fluids produced during devolatilisation of pelitic sedimentary deposits. There are no absolute ages for any of the lode deposits.

Seward Peninsula, Northwest Alaska. Rocks of the Seward Peninsula underwent a similar geological history to those of the Brooks Range prior to mid-Cretaceous time. However, unlike the Brooks Range, they were then subjected to a major thermal event. Between 110 Ma and 80 Ma (Armstrong *et al.*, 1986), plutons were intruded throughout much of the central and southeastern parts of the Seward Peninsula; amphibolite-facies assemblages occur in pelitic rocks adjacent to the plutons (Fig. 3). Also, in contrast to the Brook Range, six million ounces of placer gold (the Nome and surrounding districts) have been recovered (Koschmann and Bergendahl, 1968) in areas underlain by greenschist-facies sedimentary rocks or in beach deposits downstream from such medium-grade metamorphic rocks. Small gold-bearing quartz veins cut bluschist–greenschist-facies rocks near many of the placer deposits. The Big Hurrah mine, about 65 km east of Nome and the most significant lode gold producer in the Nome district, yielded about 27 000 oz of gold (Read and Meinert, 1986). Read and Meinert (op. cit.) interpreted fluid inclusion data from the Big Hurrah veins as being similar to those of other gold deposits that 'are generally considered to have formed as a result of regional metamorphism'.

Structural evidence indicates that gold vein formation is relatively late in the tectonic evolution of the Seward Peninsula (Craig Ford, pers. comm.). Limited geochronological data suggest that gold veining on the Seward Peninsula is temporally related to mid-Cretaceous, high-grade metamorphism and (or) igneous activity. ^{40}Ar/^{39}Ar ages for gold mineralisation of about 108.5 Ma have been determined on hydrothermal sericite from gold-bearing quartz veins at the Bluff prospect (Ford and Snee, 1993). Muscovite in adjacent schist cooled through its blocking temperature prior to 126 Ma, indicating that the dates on the sericite reflect hydrothermal mineralisation and not cooling of the host rocks (Ford and Snee, 1993).

Yukon–Tanana Upland, East-central Alaska. Placer deposits of the Yukon–Tanana upland in east-central Alaska have yielded about 11 million ounces of gold, with approximately 75% of past production coming from the Fairbanks district (Swainbank *et al.*, 1991). In addition, approximately 10 million ounces of placer gold have been recovered from the Klondike area immediately to the east in the Yukon Territory of Canada (Rushton, 1991). The source for much of the placers is likely widespread, discordant quartz veins in shears and replacement zones located throughout the greenschist- and amphibolite-facies volcaniclastic schists. Veins are commonly spatially associated with mid-Cretaceous or early Tertiary felsic to intermediate intrusive rocks and regional-scale NE-trending strike–slip faults (LeLacheur, 1991). The common occurrence of tungsten-rich skarns in marl and marble adjacent to the plutons, and syngenetic bands and disseminations of volcanogenic sulphide minerals (Metz and Hamil, 1987), has historically complicated genetic studies of gold genesis in the Yukon–Tanana region. Recently, Hollister (1991) described a low-grade, porphyritic granite-hosted gold occurrence within the Fairbanks district containing perhaps four million ounces of gold. Hollister (1991) suggested that the occurrence, known as the Fort Knox deposit, has features typical of porphyry gold systems. However, Bakke (1992) indicated an absence of porphyry style alteration and the association of gold with quartz stockworks and shear zones. Therefore, it is still uncertain whether or not the Fort Knox deposit is similar in origin to other epigenetic gold vein systems in the Yukon–Tanana upland.

Gold veining in the Yukon–Tanana upland clearly post-dates, by as much as 100 m.y., late Paleozoic through early Mesozoic convergence, deformation, and regional greenschist-facies metamorphism (Table 3). ^{40}Ar/^{39}Ar dates from metamorphic hornblende and micas throughout the Yukon–Tanana upland indicate rapid cooling of some of the upland between 188–185 Ma, and cooling from 500 to 300 °C of the remainder between 147–110 Ma (Hansen *et al.*, 1991; LeLacheur, 1991). Igneous activity was widespread from 110–85 Ma and from 70–50 Ma (Foster *et al.*, 1987), with the older thermal event perhaps occurring in response to mid-Cretaceous extension (Pavlis, 1989; Miller and Hudson, 1991; Pavlis *et al.*, 1993) or to younger terrane docking to the south. A 96 Ma K–Ar date on hydrothermal muscovite adjacent to a gold-bearing vein in a mid-Cretaceous pluton from the Fairbanks district, an 87 Ma K–Ar date on gold-related alteration in an 85–89 Ma granite from the Richardson district, and the spatial association of many of the granites of both age groups with placer deposits of east-central Alaska indicate that much of the veining is temporally related to the igneous activity (LeLacheur, 1991). K–Ar ages of 135–140 Ma on muscovite from a vein at the Sheba prospect in the Klondike district (Rushton, 1991) indicates some mineralization may be unrelated to the igneous events. More data, however, are needed before the significance of this single K–Ar age is certain.

Kuskokwim Basin, West-central Alaska. Unlike most of Alaska, rocks of west-central Alaska and of the Alaska Peninsula to the south are largely unmetamorphosed (Dusel-Bacon, 1991). Approximately three million ounces of placer gold, with about half of that amount coming from the Flat-Iditarod district, have been recovered from the Kuskokwim basin of west-central Alaska (Koschmann and Bergendahl, 1968; Swainbank *et al.*, 1991). Productive areas are underlain predominantly by Late Cretaceous flysch, with the placers and hypothesised lode sources being spatially associated with 70–60 Ma andesitic and monzonitic volcanic–plutonic complexes (Bundtzen and Miller, 1992). Few geochemical data exist from hypothesised source lodes regarding the geochemistry of the ore-forming fluids.

Epithermal cinnabar and (or) stibnite vein systems are also scattered throughout the Kuskokwim basin. Unlike the isotopically light epithermal vein systems of the Basin and Range of Western North America (Field and Fifarek, 1985), these vein systems are characterised by $\delta^{18}O$ quartz values of about 23‰ to 30‰ (Goldfarb *et al.*, 1990). At estimated quartz and metal depositional temperatures of between 150–200 °C, the ore fluids would have the same oxygen isotope composition as those that formed the mesothermal gold-bearing veins elsewhere in Alaska (see later section on stable isotope systematics). The Hg- and Sb-bearing veins probably reflect shallower and (or) lower temperature products of the same fluid type that was responsible for deposition of much of the gold in more metamorphosed environments elsewhere in Alaska. $^{40}Ar/^{39}Ar$ dates of 72–73 Ma on hydrothermal sericite from some epithermal lodes indicate veining to be roughly synchronous with the onset of Late Cretaceous magmatism in west-central Alaska (Gray *et al.*, 1992).

Willow Creek, South-central Alaska. The Willow Creek district, within the southwestern Talkeetna Mountains and about 70 km north of Anchorage, yielded approximately 624 000 oz of lode gold (Madden-McGuire *et al.*, 1989). The district lies within the Peninsular terrane (of the Wrangellia superterrane) about 8 km north of the Castle Mountain fault and about 35 km north of the Border Ranges fault system, both significant areas of Tertiary strike–slip activity. The Peninsular terrane was underthrust and added onto the southern Alaskan margin in the mid-Cretaceous. The gold district is underlain by Jurassic(?) pelitic schist and a 79–72 Ma dioritic to tonalitic pluton (Winkler, 1992), with the igneous rocks hosting most of the gold-bearing veins. K–Ar dates of 79–69 Ma (Madden-McGuire *et al.*, 1989) for biotite from the igneous rocks indicate rapid, post-crystallisation cooling. The schist was metamorphosed to amphibolite facies during the Jurassic (Winkler, 1992). K–Ar dates for adamellite and pegmatite indicate that igneous activity in the district continued until about 65 Ma (Madden-McGuire *et al.*, 1989). A hypothesised fault between the sedimentary and igneous rocks (Ray, 1954) may be a splay of the Castle Mountain fault and is spatially associated with the mineralisation. Burleigh (1987) first suggested a metamorphic origin for the ore-forming fluids in the Willow Creek district.

Conventional K–Ar dating of hydrothermal muscovite from two deposits in the Willow Creek district yielded ages of 66.3 Ma and 56.6 Ma (Madden-McGuire *et al.*, 1989). The older date correlates with the beginning of accretion and subduction of the Valdez Group, the major component of the Chugach terrane, to the south of the Border Ranges fault system. It also overlaps with the end of an extensive 15 m.y. period of felsic to intermediate plutonism on the north side of the district (Winkler, 1992). Burleigh (1987) suggests that the ore-forming fluids may have been derived from devolatilisation of the underthrusted Valdez Group turbidites. The younger date of 56.6 Ma correlates with the onset of dextral-slip on the Castle Mountain fault system (Fuchs, 1980), which perhaps focused upward migration of additional crustal fluids.

Chugach–Kenai Mountains, south-central Alaska. Small gold-bearing quartz veins within joints, faults, and shear zones occur throughout the Chugach and Kenai Mountains, located immediately north of the Gulf of Alaska (Goldfarb *et al.*, 1986). Cumulatively, the veins of the Port Valdez, Port Wells, Girdwood, Hope-Sunrise, Moose Pass, and Nuka Bay districts have yielded just over 250 000 ounces of gold, approximately half from lodes and half from placers (Goldfarb *et al.*, 1986). Mineralised structures cut both turbidites of the Chugach terrane and small, felsic to intermediate stocks and dykes that for the most part intruded the terrane soon after latest Cretaceous to earliest Tertiary accretion. Auriferous veins are restricted to greenschist-facies parts of the Chugach terrane. The veins are largely absent from areas of low-grade metamorphosed melange within the Chugach terrane, low-grade tubidites of the Prince William terrane immediately to the south, and high-grade metamorphic rocks of the Chugach terrane in the eastern Chugach Mountains. Fluid inclusion and stable isotope studies of veins from the various districts (Goldfarb *et al.*, 1986; Borden *et al.*, 1992) suggest ore fluids were produced from deeper within the Chugach terrane or from within the underthrusted Prince William terrane.

Metamorphism, magma generation, and hydrothermal activity accompanied final docking of the Chugach terrane to the southern Alaskan margin. Suites of magmas ranging from tonalite to granite were intruded into rocks of the Chugach terrane within the Chugach and Kenai Mountains between 57–50 Ma. (Plafker and Lanphere, 1974; Borden *et al.*, 1992). In the Hope-Sunrise and Port Valdez districts, K–Ar ages of 53 Ma and 52 Ma, respectively, have been reported for sericite collected from gold vein wallrocks (Mitchell *et al.*, 1981; Winkler *et al.*, 1981). We have obtained an $^{40}Ar/^{39}Ar$ age of 55.6 ± 0.2 Ma. for muscovite from the Little Creek prospect in the Nuka Bay district. Whereas gold veining in the Chugach and Kenai Mountains is roughly coeval with magmatic activity, when the two spatially overlap, the veins always cut the igneous rocks or related hornfels. None of the Eocene dykes or sills in south-central Alaska have been noted to cut mineralised veins.

In the Port Wells district, gold veins at the Granite mine cut an intrusive stock that may be part of an enigmatic group of 34–37 Ma granites restricted to the western part of Prince William Sound along the south-central margin of the Chugach Mountains. Both the veins and the host stock at the Granite mine are undated, but K–Ar biotite ages of 35.5 Ma and 36.6 Ma have been determined for igneous bodies 10–20 km to the south (Lanphere, 1966). Therefore, a second period of igneous activity, occurring at least 20 m.y. after the major Eocene thermal episode, may be coeval with additional gold veining in a part of the Chugach Mountains. The cause of the renewed thermal activity within this part of the Chugach terrane is uncertain, but it would appear that it cannot be related to compressional tectonism. The Prince William terrane is believed to have been accreted onto the Chugach terrane, underthrusted, and regionally metamorphosed by 51 ± 3 Ma (Winkler and Plafker, 1981). This was followed by a shift to a more transcurrent continental-margin setting by about 48 Ma (Plafker, 1987). Thus, unlike the Eocene gold deposits, it is very likely that those in the Port Wells district post-date the period of orthogonal convergence in south-central Alaska.

Valdez Creek, South-central Alaska. The Valdez Creek district lies within metamorphic rocks of the MacLaren Glacier metamorphic belt which exhibit steep and inverted Barrovian metamorphic gradients (Smith, 1981), and are located a few tens of kilometres south of the Alaska Range in south-central Alaska. District host rocks are probable Jurassic to Cretaceous flysch that overlaps the Wrangellia terrane to the south and the Yukon–Tanana terrane to the north. Gold mineralisation occurs near the southern margin of a 4 to 5 km thick mylonitic shear zone, termed the Valdez Creek shear zone (Davidson, 1991), within the central part of the belt. Lode and placer occurrences are restricted to rocks of the biotite zone of the greenschist facies. Valdez Creek has been Alaska's major placer gold producer over the last ten years, with most of its 400 000 ounces of production to date recovered during that time. Small, relatively unproductive, gold-bearing fissure veins are scattered upstream from the placers and within the stream bed below the placer operations. They are hosted by pelitic rocks and small, intrusive plugs and dykes of intermediate composition. Fluid inclusion and stable isotope data are consistent with a metamorphic origin for the gold-vein-forming fluids (Adams *et al.*, 1992).

Ages of gold mineralisation, based on $^{40}Ar/^{39}Ar$ analyses of muscovite from three lode occurrences in the Valdez Creek district, range from 57.6 Ma to 61.7 Ma (Adams *et al.*, 1992). These dates are significantly younger than those determined for nearby magmatic bodies, 3–5 km to the north. The Susitna batholith along the northeast edge of the Valdez Creek shear zone was intruded at 70–72 Ma and a 71–77 Ma, 1-km-thick tonalite sill occurs along the length of the shear on its northern side (Davidson, 1991). Formation of the MacLaren Glacier metamorphic belt and Valdez Creek shear zone activity accompanied emplacement of the sill. Metamorphosed rocks of the belt were subsequently cooled through the biotite closure temperature (about 280 °C) by 62 Ma (Davidson, 1991). Small dykes and stocks that host much of the veining are all undated, and it is uncertain whether they are also Late Cretaceous in age. Therefore, if gold veining is related to the Late Cretaceous high-temperature event, ore fluids must have been trapped at depth for approximately ten million years before migration to sites of vein formation. Alternatively, hydrothermal mineralisation may be related to a slightly younger thermal event responsible for the stocks and dykes along the Valdez Creek and for more localised devolatilisation activity.

Juneau Gold Belt, Southeast Alaska. The Juneau gold belt has been Alaska's largest lode gold producer, yielding approximately 6.8 million ounces of gold, largely from the Alaska–Juneau and Treadwell mines. An equal amount of gold reserves are estimated to be still present within the Alaska–Juneau and Kensington mines (Swainbank *et al.*, 1991). Deposits of the gold belt are located on either side and within a few kilometres of a major crustal struture termed the Coast Range Megalineament (Fig. 4). Auriferous veins show a strong spatial association with relatively competent igneous bodies of varied composition; these rocks are, however, many tens of millions of years older than the veining. The veins are also spatially associated with greenschist-facies rocks of an inverted metamorphic gradient of up to 8 km in thickness (Himmelberg *et al.*, 1991). Fluid inclusion and isotopic data have been interpreted to indicate ore fluids of a metamorphic origin (Goldfarb *et al.*, 1989, 1991*a*).

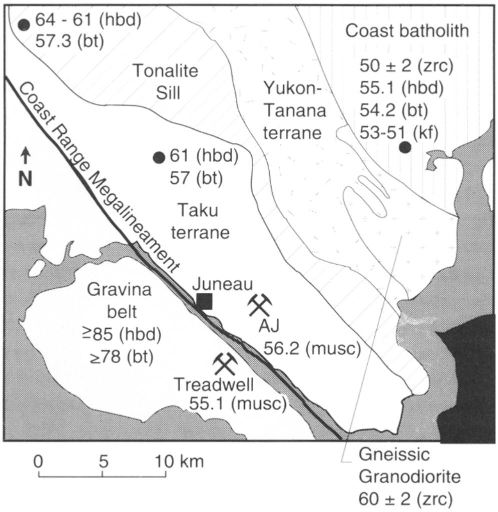


FIG. 4. Deposits of the Juneau gold belt, such as AJ (Alaska–Juneau) and Treadwell, formed at 56–55 Ma within accreted terranes that already had cooled below the 280 °C biotite-blocking temperature for argon loss (Goldfarb *et al.* 1991*b*). Gold veining is coeval with magmatic activity 20–30 km inboard and major shifts in plate motion outboard in the Pacific basin described by Lonsdale (1988). [Dates for biotite (bt), hornblende (hbd), and feldspar (kf) from igneous and metamorphic rocks determined by $^{40}Ar/^{39}Ar$ methods. Dates for zircons (zrc) from these rocks determined by U-Pb methods. Dates of gold veining determined for muscovite by $^{40}Ar/^{39}Ar$. Data are from Gehrels *et al.* (1984), Cohen *et al.* (1990), Goldfarb *et al.* (1991*b*), and Snee (unpubl. data).]

The relationship between orogeny and gold-vein formation in the Juneau gold belt has been described by Goldfarb *et al.* (1991*b*). Gold-veining along 200 km of the Coast Range Megalineament occurred between 56–55 Ma, near the end of a 60 m.y. period of orogenic activity. Relaxation along this shear zone, during a shift from orthogonal to more oblique convergence and resulting strike-slip motion, is hypothesised as having led to increased permeability and widespread fluid migration. A belt of tonalitic plutons were intruded approximately 5 km east of the megalineament between 68–61 Ma (Barker *et al.*, 1986; Wood *et al.*, 1991). The tonalities are believed to have been the primary source of heat for development of an inverted metamorphic gradient that extends westward as far as the megalineament (Himmelberg *et al.*, 1991). Extensive Eocene magmatism forming part of the Coast batholith took place from about 56–48 Ma (Barker and Arth, 1990; Snee, unpub. data), approximately 20–50 km east of the gold belt.

Chichagof, Southeast Alaska. The Chichagof district, Alaska's second largest lode district, yielded about 800 000oz of gold from quartz lodes on Chichagof Island (Reed and Coats, 1941). Almost all of the production has come from the Chichagof and Hirst–Chichagof mines hosted by Cretaceous turbidites of the Chugach terrane. The sedimentary rocks were metamorphosed to the prehnite–pumpellyite/lower greenschist facies (Dusel-Bacon *et al.*, 1991), probably during Cretaceous accretion and subduction of the Chugach terrane. A few thin dykes are associated with the Chichagof and Hirst–Chichagof deposits; one makes up much of the footwall for the latter vein system. However, no larger intrusive bodies have been recognized within 10 km of the veins. On the opposite side of the Border Ranges fault system, inboard of the Chugach terrane, minor production has come from a few small vein deposits hosted by amphibolite and diorite of the Wrangellia terrane. The amphibolite reflects a high-grade metamorphism of Paleozoic marine sedimentary and mafic volcanic rocks. It is unclear whether the metamorphism accompanied extensive Middle Jurassic to Early Cretaceous dioritic intrusive activity within the Wrangellia terrane or whether it reflects an earlier thermal event (Dusel-Bacon *et al.*, op. cit.).

The timing of gold-vein formation within the Chichagof district is uncertain. Whereas there are no dates on the age of the dykes near the Chichagof and Hirst–Chichagof veins, plutons that intrude the Chugach terrane in southeastern Alaska range from about 42–48 Ma. in age (Reifenstuhl, 1986; Karl *et al.*, 1988). Based on relationships seen in other mesothermal districts of Alaska, it is quite likely that gold genesis in this part of the Chugach terrane is related to the late middle Eocene thermal event. Since the Tertiary intrusions are restricted to the Chugach terrane, it is not known whether vein formation is coeval for deposits within both the Chugach and Wrangellia terranes on Chichagof Island.

Vein-forming fluids

Ore-fluid geochemistry. Gold-bearing quartz veins from the Seward Peninsula, Brooks Range, east-central Alaska, southern Alaska, and southeastern Alaska are characterized by a number of significant similarities (Table 2). Ore fluid salinities, generally estimated from fluid inclusion clathrate melting temperatures, are consistently between 1 and 7 wt.% equiv. NaCl; daughter minerals are never observed within ore-related inclusions. Atomic absorption analyses of leachates from fluid inclusions in quartz from the Alaska–Juneau mine containing a relatively low abundance of secondary inclusions indicate NaCl is the dominant salt. Na:(Ca + K) ratios are about 3–4, with Ca concentrations about equal to K concentrations. Microthermometric studies of fluid inclusions indicate total gas content of ore fluids generally range between 4–15 mole%. It is likely that extremely high estimates, such as inclusions with 40–60 mole% gas at Alaska–Juneau (Goldfarb *et al.*, 1989) and gas-dominant inclusions from the Nome district (Read and Meinert, 1986; Apodoca, 1992), reflect preferential trapping of the gas-rich member of an immiscible fluid pair. The dominant gas phase is almost always CO_2, with significant amounts of N_2 and CH_4 also present in the majority of deposits. Mass spectrometric analyses indicate 0.05–0.12 mole% H_2S in the gas-rich inclusions (Goldfarb *et al.*, 1989). The lack of sulphate-bearing (anhydrite and barite) and hematite–magnetite alteration assemblages, along with the abundance of pyrrhotite and arsenopyrite in many deposits, suggest relatively reduced fluids.

In most deposits within the Alaskan Cordillera, fluid inclusions containing about 4–15 mole% CO_2 and <6 wt.% equiv. NaCl were trapped in a single-phase field in P–T space above the appropriate solvus curve. Only in cases where X_{CO_2} values exceeded about 0.15 or where drastic fluctuations in pressure occurred, did fluid immiscibility accompany gold deposition. The presence of fluid immiscibility is obviously not a necessity for the formation of the gold systems; however, where it existed, it was certainly likely to have aided in ore formation. In deposits from the Nome (Read and Meinert, 1986; Apodoca, 1992) and Fairbanks (Metz and Hamil, 1987; Menzie *et al.*, 1987) districts, in a few studied veins from the Valdez Creek district (Adams *et al.*, 1992), and at the Alaska–Juneau mine in the Juneau gold belt (Goldfarb *et al.*, 1989), evidence for H_2O-CO_2 fluid immiscibility has been observed. Ashworth (1983) discussed evidence for fluid immiscibility in veins from the Chandalar/Koyukuk region; however, Rose *et al.* (1988) determined all observed inclusions to have been trapped in a one-phase field.

Fluid inclusion homogenization temperatures, and therefore minimum estimates of trapping temperatures, range from 150–380 °C for the mesothermal quartz with a general clustering between 200–300 °C. Undoubtedly, some of the

Table 2. Stable isotope and fluid inclusion data for Alaskan gold deposits.

DISTRICT	$\delta^{18}O_{quartz}$ (‰)	δD_{mica} (‰)	$\delta D_{fluid\ inc.}$ (‰)	T_{min} (°C)	P_{min} (kb)	X(gas)	Immiscibility	References
Chandalar (Brooks Range)	15.6	-	-40 to -177	250-300	0.75	.12-.14	No	1,2
Nome (Seward Peninsula)	15.4-19.2	-	-	184-360	0.8-1.0	very variable	Yes	3-5
Fairbanks/Circle (Yukon-Tanana upland)	-	-	-	290-360	-	>.08	Yes	6,7
Willow Creek (Talkeetna Mts.)	13.2-15.7	-	-71 to -142	300-325	-	.05-.06	Rarely	8
Chugach/Kenai Mountains districts	14.0-17.4	-58	-53 to -117	210-300	1.5-3.0	.08-.11	No	9-13
Valdez Creek (Clearwater Mts.)	14.9-18.4	-53, -58, -92	-117, -129	250-305	1.0-2.0	.08-.10	Sometimes	14, unpub. data
Juneau gold belt (SE Ak)	12.5-20.8	-53 to -75	-48 to -111	250	1.5	a) .03-.10 b).40-.60	No Yes	15,16
Chichagof (SE Ak)	15.7-17.3	-	-55 to -110	187-238	0.5	.04-.08	No	17, unpub. data

References:
1-Ashworth, 1983; 2-Rose et al., 1988; 3-Read and Meinert, 1986; 4-Apodoca, 1992; 5-Gamble et al., 1985; 6-Metz and Hamil, 1987; 7-Menzie et al., 1987; 8-Burleigh, 1987; 9-Goldfarb et al., 1986; 10-Borden et al., 1992; 11-Pickthorn et al., 1987; 12-Mitchell et al., 1981; 13-Pickthorn, 1984; 14-Adams et al., 1992; 15-Goldfarb et al., 1989; 16-Goldfarb et al., 1991a; 17-Karl et al., 1991.

lower temperature values reflect measurements on late, aqueous fluid inclusions that are sometimes microscopically indistinguishable from ore-related, gas-rich fluid inclusions. Deposits with observed immiscibility, however, tend to contain significant trails of aqueous fluid inclusions with relatively low homogenisation temperatures, but that appear to be ore stage. Perhaps, as described by Robert and Kelley (1987), fluid unmixing commonly pre-dates fluid migration and trapping such that corrections for pressure are required prior to determination of true trapping temperatures. High internal pressures cause many fluid inclusions from a majority of the deposits to decrepitate prior to final homogenisation. This may bias the average homogenisation temperature in many cases to unrepresentatively low values. Most estimates of true trapping temperatures are between 250–350 °C approximately. Minimum trapping pressures ranging between 0.75 kbar (Rose *et al.*, 1988) and 3 kbar (Borden *et al.*, 1992) are estimated for the majority of the mesothermal lode deposits, largely based on fluid-compositional data or the relationship between inclusion-size and required internal pressure for decrepitation (see Bodnar *et al.*, 1989).

Relative to many other ore deposit types, ore fluids from the Alaskan mesothermal deposits are distinctive. The consistently high CO_2 content of the fluids contrasts sharply with that of epithermal precious metal systems, which formed at shallower crustal levels and most likely from circulating meteoric and (or) ascending magmatic fluids. The low salinity of the ore fluids contrasts with many magmatic deposits such as skarns, porphyries, and associated polymetallic veins that often show early hydrothermal phases with 40–80 wt.% equiv. NaCl (Roedder, 1984). These hypersaline fluids are generally thought to be direct products of a separating volatile phase from a crystallizing magma. The oxidised nature of many fluids assumed to be of magmatic origin is also uncharacteristic of the Alaskan mesothermal vein-forming solutions. Concentrations of N_2 and (or) CH_4 in the Alaskan auriferous ore fluids generally reach 2–5 mole%; these volatile species are, however, rarely detected in magmatic hydrothermal systems (i.e. see articles in Hedenquist, 1992). Studies of connate waters from marine sedimentary rocks, whether of meteoric and (or) diagenetically modified seawater origin, also indicate that they are commonly brines. Therefore, a low-salinity, high-CO_2, metamorphic water field represents the most plausible source reservoir for the mesothermal ore fluids. The chemistries of the ore fluids from the Alaskan deposits are compatible with the calculated composition of a metamorphic fluid produced at greenschist–amphibolite reactions within clastic metasedimentary (±mafic volcanic) rock sequences (Fyfe *et al.*, 1978; Powell *et al.*, 1991).

Stable isotope systematics. Oxygen and hydrogen isotope systematics of the Alaskan mesothermal gold systems (Fig. 5) clearly suggest that the

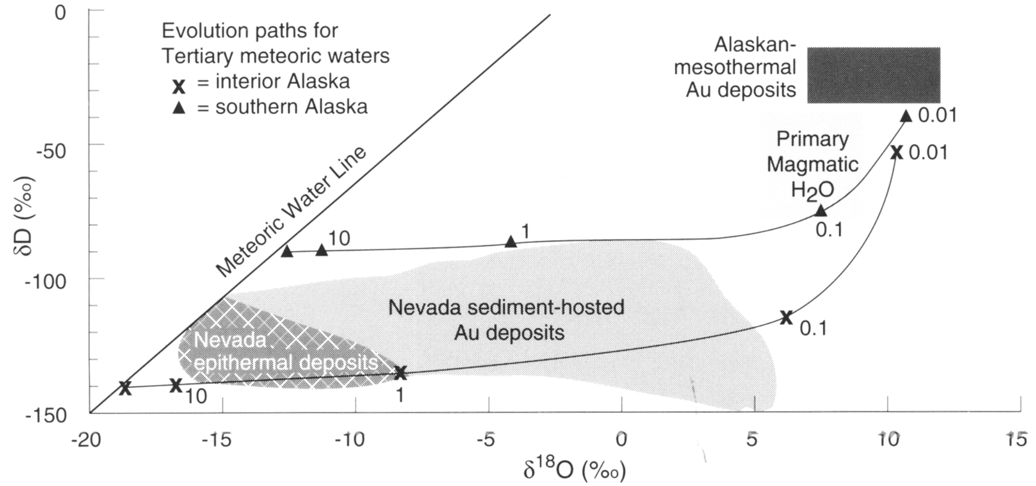


FIG. 5. Plot of $\delta^{18}O$ versus δD for ore fluids from mesothermal gold deposits in Alaska and other hydrothermal gold systems in Nevada. Values of 10, 1, 0.1 and 0.01 refer to fluid : rock ratios. A calculated fluid-evolution path, assuming convection through clastic sedimentary rocks, indicates that the Alaskan deposits could not have formed from meteoric water circulation except under conditions of unreasonably low water : rock mass ratios. On the other hand, the broad range in $\delta^{18}O$ for Nevada systems is what would be expected for meteoric water hydrothermal systems, with heaviest $\delta^{18}O$ values indicative of increasing rock dominance.

ore fluids were derived from devolatilisation reactions within the metamorphic piles (Pickthorn *et al.*, 1987; Goldfarb *et al.*, 1991*a*). Oxygen isotope data for auriferous quartz from more than 50 mesothermal deposits throughout south-eastern (Goldfarb *et al.*, 1991*a*), south-central (Goldfarb *et al.*, 1986; Burleigh, 1987; Borden *et al.*, 1992; Adams *et al.*, 1992), northeastern (Rose *et al.*, 1988), and northwestern (Gamble *et al.*, 1985) Alaska generally cluster between about 14–19‰, indicative of a consistent $\delta^{18}O_{fluid}$ between about 7–12‰ at 300 °C. Whereas stable isotope studies are lacking for east-central Alaska, Rushton (1991) reports similar values to the above for the Klondike district in the adjacent Yukon Territory.

For the most part, similar values for igneous rock- and sedimentary rock-hosted vein quartz indicate fluid-dominant hydrothermal systems—that is, $\delta^{18}O$ values of convecting fluids are largely unaffected by reaction with aquifer walls. Values of $\delta^{18}O_{quartz}$ range from 14.9–18.4‰ for gold-bearing veins in the Valdez Creek district, with little noticeable difference between argillite-hosted and igneous-rock-hosted veins. In the Port Valdez district, sedimentary-rock-hosted veins range in $\delta^{18}O$ between 14–17‰, and the one lode hosted in a small stock, the Rough and Tough mine, has a $\delta^{18}O_{quartz}$ value of 16.2‰. Along the Juneau gold belt, the majority of the metagabbro-hosted veins at the Alaska–Juneau mine, monzodiorite-hosted veins at the Treadwell mine, and phyllite-hosted veins at the EPU and Sumdum Chief mines, all range between 17–19‰. Oxygen isotope values for mineralised quartz from the Willow Creek district range from 15.3–15.8‰ for schist-hosted veins and from 13.2–15.6‰ for plutonic rock-hosted veins (Burleigh, 1987; Madden-McGuire *et al.*, 1989), also suggesting a fluid-dominant hydrothermal system at the location of ore deposition.

Results of more than 100 analyses of gold-bearing quartz rarely show $\delta^{18}O$ values below 14‰. In the Juneau gold belt, a minority of the veins from the Kensington deposit shows $\delta^{18}O_{quartz}$ values of 12–13‰; the majority range from 15–16‰, and the monzodiorite host stock has a value of 7.4‰. This may be one example where fluid–rock interaction has caused a minor shift in $\delta^{18}O_{fluid}$ along part of the hydrothermal flow path because there are no notable differences in fluid inclusion homogenisation temperatures between the two vein groups.

The most ^{18}O-depleted gold-bearing quartz vein reported from Alaska is a sample from the Big Hurrah mine in the Nome district. A $\delta^{18}O_{quartz}$ value of 10.2‰ (for 'quartz from the mineralized area' at the mine) contrasts sharply with other values of 15.4–19.2‰ for the Nome region (Gamble *et al.*, 1985). The latter values are consistent with a metamorphic ore fluid, whereas, assuming quartz precipitation at 300 °C, the former isotopically lighter value is incompatible with a metamorphic fluid. We have, however, also analysed gold-bearing quartz from the Big Hurrah mine and obtained a $\delta^{18}O$ value of 18.1‰. Therefore, the significance of the anomalously light measurement by Gamble *et al.* (1985) is questionable.

The oxygen data, as a group, can be interpreted in two very different manners: (1) isotopically heavy fluids both originated within, and were channelled upward in the mid-crust, or (2) isotopically light surface fluids circulated downward to mid-crustal levels under relatively low water:rock mass ratios. We believe the data indicate the former, such that hydrothermal systems were strongly channelled and show little $\delta^{18}O$ shift from original compositions. In source regions, prograde metamorphic fluids fill pore spaces and obtain isotopically heavy compositions characteristic of the metasedimentary-rock-dominant pile. With the onset of hydrothermal activity, perhaps initiated by thermal perturbations of the porous rock, propagation of fracture networks will localise fluid flow into highly permeable conduits. Under such locally fluid-dominant conditions, crustal conduits should have sufficiently large prograde fluid volumes, so that the fluid phase is not depleted by retrograde mineral reactions. Isotopic composition of the fluid will remain unchanged along the length of its flow path and at sites of mineral precipitation. Relatively consistent $\delta^{18}O$ values for quartz in variable vein host lithologies supports such a hypothesis.

Alternatively, it has been argued that the uniformity in oxygen data (especially when considered along with associated δD data) is characteristic of rock-dominated, meteoric water, hydrothermal systems such that originally light $\delta^{18}O_{fluid}$ values are altered by the metasedimentary rocks of the host terranes (Nesbitt, 1990). To get the required oxygen shift of 25–30‰ during the hypothesised deep circulation of surface waters, however, would require very low water: rock ratios (<0.1) at 300 °C *within all Alaskan gold districts* (Fig. 5). Under such a situation, much of the descending water will rehydrate metamorphic minerals within the uplifting and cooling metamorphic terranes. (The only way to escape such a scenario would be to assume that meteroric fluids were strongly channelled during downward flow, only became more pervasive at depth, leading to extensive interaction with rock and shifting isotope compositions, and finally were channelled back into a few major conduits during upward flow. It is difficult, however, to imagine conditions which could lead consistently to such a mechanism of fluid flow.) More significantly, it seems unlikely that all mesothermal vein-forming fluids in Alsaka, as well as those from elsewhere in the world (see Kerrich, 1989), could be shifted from relatively ^{18}O-depleted meteoric water values to $\delta^{18}O$ compositions exceeding +5‰. If the ore fluids are not derived from deep crustal metamorphic processes, we expect at least some variation in $\delta^{18}O$ trending toward original, lighter isotopic values. The extensive vein networks associated with many of the mesothermal systems and association of the larger deposits with major crustal structures are inconsistent with required rock-dominant conditions in the meteoric water model.

If we conclude that the narrow range of $\delta^{18}O$ for Alaskan deposits reflects high water : rock ratios along channelled flow paths, then can such a range in stable isotope composition be clearly shown as being distinctive from more rock-dominant, meteoric water-rich hydrothermal systems? Epithermal and sediment-hosted gold deposits trending away from the meteoric water line (Fig. 5), such as seen in the Basin and Range of Western North America (Field and Fifarek, 1985), provide a good example of the much wider range in $\delta^{18}O$ that should be observed for ore systems dominated by fluids of meteoric origin. These deposits from the Basin and Range exhibit an isotopic pattern reflecting decreasing water- : rock ratios (and perhaps some fluid mixing). With increased rock-dominance, there is a shift in oxygen isotope composition away from original fluid values (in this case meteoric water) during exchange with isotopically heavier rocks (Fig. 5). If, as in Nesbitt (1990), it is assumed that the Alaskan mesothermal deposits were formed from meteoric water under low water : rock conditions, then the Nevada gold systems must be products of hydrothermal circulation under significantly greater water : rock regimes. This is because the mesothermal systems would have to be shifted much further to the right of the meteoric water line, to much greater enrichments of ^{18}O than would the Nevada deposits. This seems highly unlikely, based on the much more disseminated or stringy nature of the ore and lack of major crustal structures directly hosting many of the Nevada deposits.

Hydrogen isotope data from many Alaskan deposits also are suggestive of metamorphic fluid sources. Values of δD for hydrothermal sericite and chlorite from auriferous quartz in the Valdez Creek, Port Valdez, and Juneau gold belt districts consistently range between −53‰ and −75‰. Using a water–chlorite fractionation of 40‰ (Taylor, 1974) and an extrapolated water– muscovite fractionation of 40‰ in data from Suzuoki and Epstein (1976), ore fluids at 300 °C would have ranged in δD between −15‰ and −35‰ (Fig. 5). An anomalous δD value of −92‰ for sericite from the Timberline Creek mine in the Valdez Creek district (Adams *et al.*, 1992) is 35–40‰ lighter than those from other mines in the district. This likely reflects some post-depositional isotopic exchange with meteoric fluids during uplift. Alternatively, it could indicate derivation of ore fluids from different sources, such as devolatilisation reactions within two distinct lithologic units. In the Klondike district of the Yukon–Tanana upland, Rushton (1991) noted muscovite with a δD of −185‰ from one mine. However, as pointed out by Taylor *et al.* (1991), hydrothermal micas associated with mesothermal gold in British Columbia and the Yukon Territory are characterised by both isotopically light and heavy values. The more D-depleted group is best interpreted as reflecting isotopic exchange during regional uplift between originally heavier micas and meteoric waters. Magaritz and Taylor (1976) documented extensive meteoric water circulation associated with widespread Eocene extension inboard of Alaska.

Fluid inclusion waters extracted from mesothermal vein quartz throughout Alaska exhibit a range in δD from values close to those calculated from the micas to values approximating present-day meteoric waters (Table 2). These clearly reflect contamination of ore-related fluids with many other generations of fluids trapped in trails of late inclusions and are generally unrepresentative of ore fluid values (Pickthorn *et al.*, 1987; Goldfarb *et al.*, 1991*a*; Kyser and Kerrich, 1991). Ranges in δD of 55–71‰ for quartz vein samples within the Willow Creek (Burleigh, 1987), Chugach–Kenai Mountains (Mitchell *et al.*, 1981; Pickthorn, 1984; Borden *et al.*, 1992), and Chichagof (Karl *et al.*, 1991) districts are too wide to solely reflect a single fluid type at a single latitude. In a few cases, δD values of fluid inclusion waters extracted from the relatively least sheared gold veins in a district are believed to approach primary ore fluid values. For gold deposits in the Brooks Range, values of δD for fluid inclusion waters released from thermally decrepitated quartz ranged from −40 to −72‰ in samples with a high abundance of primary inclusions and from −156 to −177‰ in more intensely sheared ribbon veins (Rose, pers. comm.). Similarly, Goldfarb *et al.* (1991*a*) indicated δD values of −48‰ for inclusion waters from relatively undeformed gold-bearing quartz to −111‰ for waters from highly deformed veins from the Juneau gold belt.

Cordilleran tectonics and mesothermal vein formation

Orogenic gold deposits. All of southeast Alaska and interior Alaska south of the Denali fault system is composed of numerous terranes accreted to and subducted below the craton in Cretaceous and Tertiary time. Geochronological data from the resulting orogenic belts indicate a close temporal association between gold-vein formation and periods of high heat flow (Table 3). Whereas ore-forming fluids were derived from metamorphism of predominantly sedimentary rock packages, plutonic rocks may have provided the necessary heat for devolatilisation reactions. On the other hand, metamorphic devolatilisation of sedimentary rocks and igneous activity may just be coeval events reflecting the same high-temperature tectonic episode. A distinction between the two possibilities is problematic since both are likely to have occurred simultaneously. What has become clear, especially with a wealth of new age data collected over the last few years, is the close temporal relationship between high-*T* tectonic deformation, igneous activity, and gold mineralisation.

Gold-vein formation and magmatic activity in southern Alaska were concentrated between Campanian and middle Eocene time. Farallon and Kula plate subduction below southeastern and south-central Alaska led to the development of the 72–48 Ma Coast and 74–55 Ma Alaska Range continental margin batholiths (Barker *et al.*, 1986; Reed *et al.*, 1983). Gold veining, temporally and often spatially correlated with more localised magmatic activity, occurred at depths of at least 3–5 km throughout the accretionary prism of the forearc (Fig. 6*b*). It is likely that fluid released from dehydrating minerals within the downgoing oceanic floor and/or overlying rocks mobilised and concentrated gold, and also triggered melting of overlying rocks. Rising anatectic melts would have led to additional prograde metamorphism of the sedimentary prism and release of metamorphic fluids.

In south-central Alaska, most of the gold veining occurred between 66–56 Ma in the Willow Creek district, 56–52 Ma in the Chugach and Kenai Mountains, and 62–57 Ma. in the Valdez Creek district. Mesothermal vein formation occurred at depth from proximal to the continental margin to as far as 250 km inboard. During this time, the Kula plate was still subducting below the continental margin and the outboard part of the Chugach terrane and the adjacent Prince William terrane were being offscraped to form the currently exposed accretionary prism. As summarised by Barker *et al.* (1992), much of the coeval high-temperature magmatic activity in the forearc could reflect underthrusting of a triple junction, leaky transform faults, or parts of an oceanic ridge system, or the upwelling of hot asthenosphere through a slab window.

Gold deposits of the Juneau gold belt in southeastern Alaska formed about 125 km inboard of the continental margin at about 56–55 Ma. The veining episode correlates with the final stages of orthogonal convergence and a shift to a more oblique collisional component (Lonsdale, 1988). Unlike south-central Alaska, coeval magmatic activity is not spatially associated with gold veining. However, igneous activity was ongoing in the Coast Batholith at this time, only about 20 km inboard from the gold belt. The

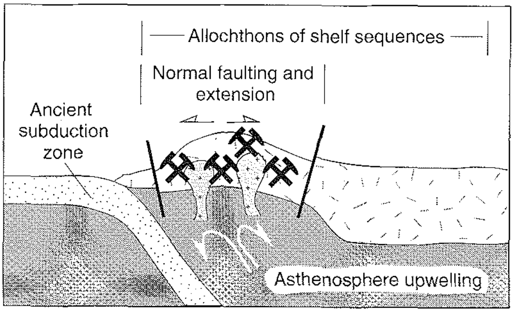
Table 3. Geochronological data for Alaskan gold deposits..

DISTRICT	HOST TERRANE	COLLISIONAL OROGENESIS	POST-COLLISIONAL MAGMATISM	GOLD-VEIN FORMATION	REFERENCES
Chandalar (Brooks Range)	Arctic Alaska	M. Jur. to earliest Cret.	none	Albian(?)	1,2,4
Nome (Seward Peninsula)	Seward	M. Jur. to earliest Cret.	100-80 Ma	108.5 Ma	1,3-6
Fairbanks/Circle (Yukon-Tanana upland)	Yukon-Tanana	L. Permian to Jur.	110-85 Ma, 70-50 Ma	96-87 Ma	7-9
Willow Creek (Talkeetna Mts.)	Peninsular	Cret. to E. Eocene	75-66 Ma	67-56 Ma	10,11
Chugach/Kenai Mountains districts	Chugach	Late Cret. to E. Eocene	57-50 Ma, 37-34 Ma	56-52 Ma, Oligocene(?)	12-17
Valdez Creek (Clearwater Mts.)	Gravina-Nutzotin(?)	Cret. to E. Eocene	77-70 Ma	62-57 Ma	18-20
Juneau gold belt (SE Ak)	Taku, Gravina-Nutzotin	*mid*-Cret. to E. Eocene	68-61 Ma, 56-48 Ma	56-55 Ma	21,22
Chichagof (SE Ak)	Chugach, Wrangellia	mid-Cret. to E. Eocene	48-42 Ma	?	23,24

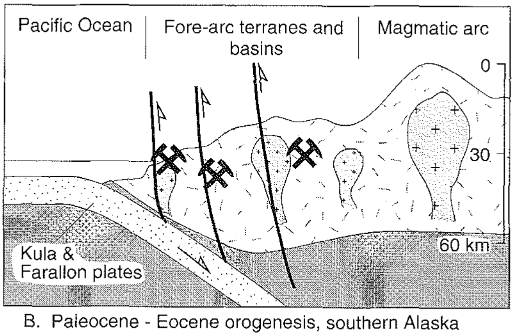
References:
1-Armstrong et al., 1986; 2-Dillion et al., 1987; 3-Patrick and Evans, 1989; 4-Miller and Hudson, 1991; 5-Thurston, 1985; 6-Ford and Snee, 1993; 7-Hansen et al., 1991, 8-Foster et al.,1987; 9-LeLacheur, 1991; 10-Winkler, 1992; 11-Madden-McGuire et al., 1989; 12-Plafker and Lanphere, 1974; 13-Borden et al., 1992; 14-Mitchell et al., 1981; 15-Winkler et al., 1981; 16-Lanphere, 1966; 17-Plafker, 1987; 18 Adams et al., 1992, 19-Davidson, 1991; 20-Smith, 1981; 21-Goldfarb et al., 1991b; 21-Barker and Arth, 1990; 23-Riefenstuhl, 1986; 24-Karl et al., 1991.

deposits of the Chichagof district occur further outboard, directly along the continental margin. Because no dates are available from this district, it is uncertain whether the veins also formed during periods of high heat flux and contractional orogenesis.

Vein formation during orogenic collapse. Geological relationships and limited geochronological data suggest that gold-veining post-dates convergence, obduction of oceanic crust, and blueschist-facies metamorphism of much of interior Alaska by at least 50 million years. The veins are associated with a period of Mid- to Late Cretaceous high-heat flow, possibly triggered by extension-related, crustal thinning (Fig. 6*a*), and anatexis (Miller and Hudson, 1991; Pavlis *et al.*, 1993). Prior to these high-temperature events within the Seward Peninsula, Yukon–Tanana upland, and Ruby Geanticline, regional metamorphic temperatures would not have exceeded about 450–500 °C. Any metamorphic fluids released during Middle Jurassic to Early Cretaceous collisional orogenesis were evidently incapable of transporting significant gold, as indicated by the general lack of gold-bearing vein quartz throughout almost the entire southern Brooks Range. Relatively limited volumes of metamorphic fluid associated with the low-temperature blueschist events may be, in part, responsible for the absence of Middle Jurassic to Early Cretaceous arc magmatism. During such a relatively 'dry' orogensis, extremely high crustal temperatures would be required prior to magma generation.



A. Middle Cretaceous orogenic collapse, interior and northern Alaska



B. Paleocene - Eocene orogenesis, southern Alaska

FIG. 6. (*a*) Jurassic through Early Cretaceous orogenesis within interior Alaska was characterised by obduction of the oceanic floor, blueschist metamorphism, and a lack of magmatic activity and gold veining. High-temperature thermal episodes and related mineralisation occurred some 50–100 m.y. after collision, during a period of crustal thinning and likely extension that accompanied orogenic collapse. (*b*) Gold deposits along the southern and southeastern Alaskan continental margin formed coevally with early Tertiary subduction, orogenesis, and magmatic arc activity.

Absolute age data are generally unavailable for lode-gold deposits of northern Alaska. This largely reflects the lack of datable material from both the Nome district and the Chandalar–Koyukuk region. A few dates, now available for a small vein occurrence in the Nome district (Ford and Snee, 1993), suggest veining is coeval with the onset of high-temperature episodes. Also, a strong spatial association in northern Alaska between Cretaceous magmatic rocks and areas of abundant placer gold indicates mineralisation is genetically related to high-T, Cretaceous thermal events and thus was a relatively late event in the tectonic history of the region.

The Seward Peninsula is the only part of the Brooks Range blueschist–greenschist metamorphic belt to have been directly affected by Cretaceous magmatism and high-temperature metamorphism. Gold veining is evidently associated with the high-temperature event. It is probably no coincidence that the only major gold accumulation across a 1200 km long metamorphic belt is spatially associated with rocks affected by the only high-temperature event evidenced within the belt. Prior to the Cretaceous thermal event, Precambrian(?) and Paleozoic rocks of the Seward Peninsula experienced maximum temperatures of no more than 460 ± 30 °C (Patrick and Evans, 1989). Albian to Campanian anatectic gneisses, granites, and high-grade metamorphic rocks make up the core of the Seward Peninsula, with isograds defining a field gradient of approximately 100 °C/km (Miller *et al.*, 1992). The exceptionally rich beach placers at Nome are situated about 40 km south of the high-grade metamorphic rocks; small, gold-bearing quartz veins, however, are widespread in the lower grade metamorphic rocks, extending from Nome to areas immediately adjacent to the higher grade rocks. We propose that these veins formed as products of a metamorphic fluid that migrated away from the central part of the Seward Peninsula during Barrovian-series metamorphism.

Greenschist-facies rocks of the Chandalar–Koyukuk gold region in the eastern Brooks Range show no such high-*T* overprint on Early Cretaceous blueschist–greenschist assemblages. However, it is noteworthy that the contact between the Brooks Range fold and thrust belt and the Ruby Geanticline lies only about 30–40 km directly south of the gold occurrences. Numerous Albian-age plutons were intruded along the northern edge of the geanticline (Patton and Box, 1989; Roeske *et al.*, in press) in probable contact with the south-dipping Angayucham thrust fault system. Schists surrounding these plutons underwent low-pressure amphibolite-facies metamorphism at temperatures of at least 500 °C, perhaps during the early stages of Cretaceous igneous activity (Dusel-Bacon *et al.*, 1989; Roeske *et al.*, in press). The Angayucham fault system probably continued northward prior to final unroofing of the southern Brooks Range to a location somewhere above the present Chandalar and Koyukuk districts. Therefore, the Angayucham fault system could have been an important conduit for hot fluids released during the mid-Cretaceous thermal event.

Absolute ages for gold mineralisation are better constrained within the Yukon–Tanana upland. As stated earlier, K–Ar ages for vein formation from the Fairbanks district indicate that much of the vein formation occurred in the early Late Cretaceous. These data overlap a 25 m.y. period of plutonic activity during which many sedimentary assemblages in east-central Alaska were first subjected to high crustal heat flow. As was suggested for northern Alaska, localized prograde-metamorphic reactions that occurred long after collision and orogeny are the suspected source of hydrothermal fluid production.

Conclusions

Gold-vein formation was widespread throughout the accreted terranes of southern Alaska, a part of the northern Codillera characterised by subduction of oceanic crust below the offscraped sediment-dominated wedge and the adjacent autochthonous continental margin. Anomalous thermal conditions are well-recognised features associated with subduction zones. In southern Alaska, a Cretaceous through Eocene continental-margin arc composed of the Alaska–Aleutian Range, Talkeetna Mountains batholith, Kluane arc, and Coast batholith, marks the inboard core of the orogen. Palaeogene anataxis within the flyschoid rocks of the suspect terranes outboard of the arc (Barker *et al.*, 1992) reflects additional high-temperature episodes. Most rocks exposed within the accreted terranes have been metamorphosed to the greenschist facies along typical Barrovian-series gradients. Locally, extremely high geothermal gradients have been superimposed on the metamorphosed rocks perhaps reflecting more classical contact-metamorphic events. Gold-bearing quartz veins were generally deposited within the contractional orogen within a few million years or less of subduction-related magmatism.

Northern and interior Alaska were subjected to a compressional orogen characterised by obduction of oceanic crust. The resultant relatively shallow angle underthrusting led to deformation and crustal thickening, but not magmatism. The absence of moderate- to high-*T* thermal activity may reflect the lack of development of a hot asthenosphere wedge, such as is commonly developed above the underplated slab in compressional regimes characterised by subduction of oceanic crust. It was not until mid-Cretaceous crustal anatexis, perhaps triggered by extensional decompression of the previously underplated allochthons (Miller and Hudson, 1991), that temperatures of currently exposed crustal rocks reached 450 °C locally. Gold-bearing quartz veins were most likely formed during this high-temperature event, approximately 100 m.y. subsequent to the main contractional deformation in the Yukon–Tanana upland and 50 m.y. after such an episode in northern Alaska.

The geochemistry of the hydrothermal fluids provides considerable evidence for their origin via the breakdown of volatile-bearing mineral phases during prograde metamorphism. Progressive metamorphism of an average pelite will release about 5 wt.% H_2O and CO_2 (Walther and Orville, 1982). Most fluid release will occur at discrete metamorphic-facies boundaries, spread across a broad range of crustal temperatures extending from zeolite- to granulite-facies conditions (Fyfe *et al.*, 1978). The absence of gold veining during blueschist–greenschist-facies events over much of interior Alaska, especially implied by the lack of gold across most of the southern Brooks Range, documents the higher temperatures required before gold is successfully extracted by metamorphic fluids. Crustal temperatures of perhaps 450–500 °C, corresponding to the greenschist–amphibolite transition, appear to be needed before mesothermal, gold-bearing hydrothermal systems are established in Cordilleran terranes. Such relatively high temperatures necessary for gold extraction have also been hypothesised for mineralised systems in Archean greenstone belts using mineral equilibria models (Powell *et al.*, 1991) and from the observation that temperature estimates for vein formation extend up to this transition (Fyfe and Kerrich, 1984).

An obvious cause for the greater efficiency of gold extraction at temperatures ⩾450 °C might be increased gold solubility at the higher temperatures. Very little experimental data exist for gold solubility in excess of about 300 °C. However, theoretical calculations by Romberger (1986) indicate that gold in low-salinity, reduced sulphur-containing solutions shows a marked decrease in solubility at temperatures above 300 °C. Therefore, an alternative scenario is that significant amounts of reduced-sulphur ligands do not become available to hydrothermal solutions until relatively higher temperatures. The pyrite-to-pyrrhotite metamorphic reaction could release significant amounts of reduced sulphur to the metamorphic fluid near the greenschist–amphibolite boundary. Much of the leachable gold within the accreted terranes may also be tied up in sulphide phases and may not become leachable until released during significant periods of desulphidisation.

It is extremely clear that spatial and temporal associations commonly exist between gold veining and igneous activity. Both are products of the same anomalous heat flux. The importance of a high crustal geothermal gradient in the genesis of mesothermal gold has recently been stressed for Victorian (Phillips, 1991) and Archean (Powell *et al.*, 1991) examples. Devolatilisation may be a consequence of a widespread regional metamorphism (i.e. Chugach terrane); it may be, in part, a product of regional magmatic heat flow (i.e. tonalite belt and (or) Coast batholith east of the Juneau gold belt); or it may be the result of localized contact metamorphism (i.e. Fairbanks district). It may be impossible to distinguish between rocks affected by true contact metamorphism and by regional metamorphism; the *P–T* conditions of each merge imperceptibly into each other (Pattison and Tracy, 1991) such that any real differences may be meaningless.

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