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# Orogenic gold and evolution of the Cordilleran orogen

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## ABSTRACT

**Orogenic gold deposits are located adjacent to deep-crustal fault zones, which commonly parallel continental-margin magmatic arcs in crustally thickened parts of the North American Cordilleran orogen. The most important Cretaceous to Eocene deposits are located 100-200 km landward of the edge of the continent and within allochthonous oceanic terranes that were accreted to the craton 35-80 m.y. prior to gold deposition. Gold provinces are sited in the fore-arc (Juneau gold belt, Sierra foothills), back-arc (Bridge River), and arc margins (Willow Creek). In all provinces, older intrusions define structurally favorable host rocks for many of the larger gold resources. Arc magmatism in the gold provinces began 5-20 m.y. prior to hydrothermal activity, except in the Sierra foothills where the widespread gold formation pre-dates the earliest phases of the Sierra batholith by at least a few million years. The one temporally consistent, major tectonic feature in all gold provinces is the correlation of ore formation with transpression and related uplift along the fault systems. These critical events for the generation of Cordilleran gold provinces specifically included: (1) a ca. 125 Ma change from sinistral to dextral strike-slip along the faults of the Sierra foothills, (2) a ca. 55 Ma shift from a compressional to transpressional regime within the terranes of the Juneau gold belt, (3) the ca. 66 Ma onset of dextral slip on northern splays of the Border Ranges fault system in the Willow Creek district, and (4) the ca. 66 Ma initiation of a transpressive regime and dextral slip along splays of the Yalakom fault system within the Bridge River district. Changing stress fields and associated transpressive tectonics are perhaps the most critical feature for the development of orogenic gold provinces within Cordilleran-type orogens.**

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## INTRODUCTION

Economically significant orogenic gold deposits of Mesozoic-Cenozoic age are almost exclusively restricted to the circum-Pacific, within orogens that define the most active continental margins subsequent to Pangea breakup (e.g., Goldfarb et al., 1998, 2001). As much as 200 Moz of this gold endowment are part of the past production, new resources, and associated placer accumulations recorded within the North American Cordilleran orogen. These orogenic gold deposits formed between ca. 180 and 50 Ma and over a distance of more than 5000 km from Nome, Alaska, through the Yukon and British Columbia, to the Sierra Foothills of California (Fig. 1).

Ore deposits in the Cordilleran orogen older than about 180 Ma represent either products of mostly syngenetic hydrothermal systems that were active in the platform/shelf environment of the ancestral North America miogeocline, or epigenetic systems that developed in distal oceanic arcs and continental fragments prior to their accretion to the North American craton. The initiation of compressional tectonism along the continental margin began with the late Paleozoic to Early Triassic obduction of allochthons of oceanic crust and overlying sediment above the rocks of the miogeocline (Oldow et al., 1989). But it wasn't until the Late Triassic, when subduction of oceanic terranes first occurred along the margin and moderate- to high-temperature Cordilleran orogenesis was thus initiated, that a favorable tectonothermal regime began to be established for the generation of orogenic gold deposits at mid-crustal levels.

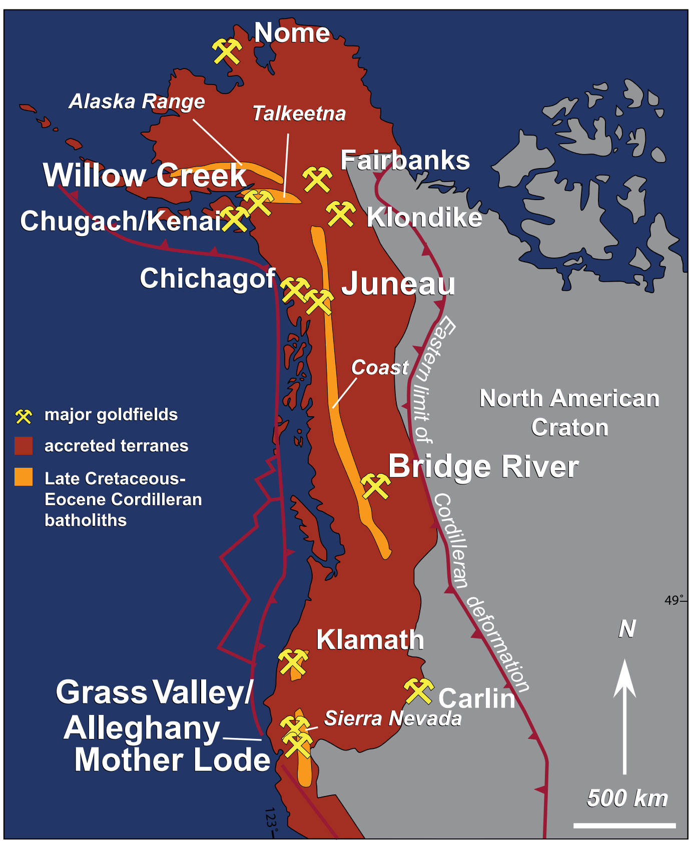


Figure 1. Orogenic gold provinces of the Cordilleran orogen. Major gold resources are located along terrane-bounding fault zones within a few tens of kilometers of the main Cordilleran continental margin batholiths. They occur seaward (Juneau gold belt, California goldfields) of the magmatic arc, landward of the arc (Bridge River), or within the margin of the arc (Willow Creek).

Within 10-20 million years of the onset of subduction and accretion, large areas of the mid-crust within the growing margin began to experience a significant rise in geotherms due to the complex interplay among a number of factors. These likely would include, to at least some degree, release of radioactive heat from accreted material, shear heating, heating from massive fluid flux, crustal thickening, ridge subduction, and slab rollback (Kerrich et al., 2000; Goldfarb et al., 2005). Typical Barrovian P-T conditions, leading to a "deeper-later" metamorphic style (e.g., Stuwe, 1998), caused release of enormous fluid volumes; perhaps as much as five volume percent of the accreted and/or underplated material was converted to a low salinity, C-O-H-N-S fluid during metamorphic reactions. These fluids, anomalous in As, Au, B, Hg, Sb, and W, were focused along deep crustal faults, commonly terrane-bounding structures in the crustally thickened parts of the orogen, during seismic events associated with changes in regional stress fields. Resulting orogenic gold deposits formed throughout the Cordillera at depths of 3-20 km (Groves et al., 1998; Goldfarb et al., 2005).

The oldest gold lodes are those of Middle-Late Jurassic in the Canadian Cordillera (Goldfarb et al., 1998). Early Cretaceous ores characterize the Sierra Foothills (Böhlke and Kistler, 1986), mid-Cretaceous deposits occur in interior Alaska (McCoy et al., 1997), and Paleocene-Eocene ores are exposed along the present-day Gulf of Alaska (Goldfarb et al., 1997). Orogenic gold deposits formed during the most recent 50 m.y. certainly exist, but they have yet to be unroofed. Mercury and antimony deposits within the Cordillera, which are characterized by anomalous $CO_2$ and $^{18}O$ concentrations, define shallow levels of the hydrothermal systems that may overlie some of the still buried orogenic gold lodes (Groves et al., 1998; Goldfarb et al, 2005).

The Cordilleran orogen of western North America represents a relatively young, well-studied, and well-dated orogen. Major tectonic events, particularly regional structural and magmatic episodes, are thus well-constrained. As a consequence, the hydrothermal events that were responsible for formation of the metalliferous systems, comprised of orogenic gold deposits and any associated mercury-antimony deposits, can be relatively precisely correlated, both spatially and temporally, to the major processes of orogeny in this part of the circum-Pacific. Such findings will subsequently allow for a better overall understanding of how, in general, mineral deposits that formed from metamorphic processes relate to major tectonic processes active during orogeny.

## OROGENIC GOLD IN THE NORTH AMERICAN CORDILLERA

Gold deposits of the Cordilleran orogen range in age from ca. 180 to 50 Ma (Goldfarb et al., 1998). Many of the ore-hosting districts in interior Alaska (e.g., Fairbanks, Seward Peninsula) or western Canada (e.g., Klondike, Atlin) have a relatively complex deformational and magmatic history because of the tens of millions of years of outboard collision. The locations and geometries of the subduction-related arcs in these areas may be difficult to define and much of the initial gold resource may be eroded into placer accumulations. Relationships between lode deposits and orogenesis may thus be difficult to define in the older and more landward parts of the orogen. Furthermore, parts of the orogen not directly associated with a large ocean closure generally lack an abundance of amalgamated accreted terranes and arcs, and thus deep-crustal faults or terrane sutures (e.g., Seward Peninsula, Klondike), making such environments less amenable to fluid focusing and large lode concentrations (Leahy et al., 2005). In more present-day coastal areas of western North America where relatively young Cordilleran batholiths can still be well-defined, widespread transpression of these uplifted and thickened central parts of the orogen, concentrated along the deep crustal fault zones between dozens of allochthonous terranes along the Pacfic rim, characterizes the late Mesozoic and early Tertiary (Oldow et al., 1989). These areas exhibit the best documented temporal relationships between deformation, magmatism, and orogenic gold deposit formation (Fig. 1).

We describe below these critical tectonic features for the major orogenic gold provinces spatially associated with the Cordilleran batholiths. These include the Juneau gold belt and Sierra foothills province seaward of the Cordilleran arc, the Bridge River district landward of the arc, and the Willow Creek district within the arc itself.

### Sierra Foothills gold province, central California

The 300-km-long Sierra foothills gold province (Fig. 2) is the most endowed part of the Cordilleran orogen. Gold deposits are located adjacent to first-order transcrustal fault zones in a series of north-south-trending accreted terranes and overlap assemblages, which are located on the western side of the Sierra Nevada batholith. This forearc setting within an accretionary orogen is the most common tectonic setting for the formation of productive orogenic gold deposits (Groves et al., 1998, 2003). More than 40 Moz of historical gold production has come from the Sierra foothills lode systems, with about 80-90 percent of this production concentrated in (1) the 195-km-long x 1.5-km-wide Mother Lode belt (Knopf, 1929), (2) the Alleghany district, and (3) the Grass Valley district. Much of the ore in the Mother Lode belt is spatially associated with serpentinized ultramafic rocks, which are abundant along the main fault zones. The Idaho-Maryland and Empire deposits in the Grass Valley district were the largest past-producing

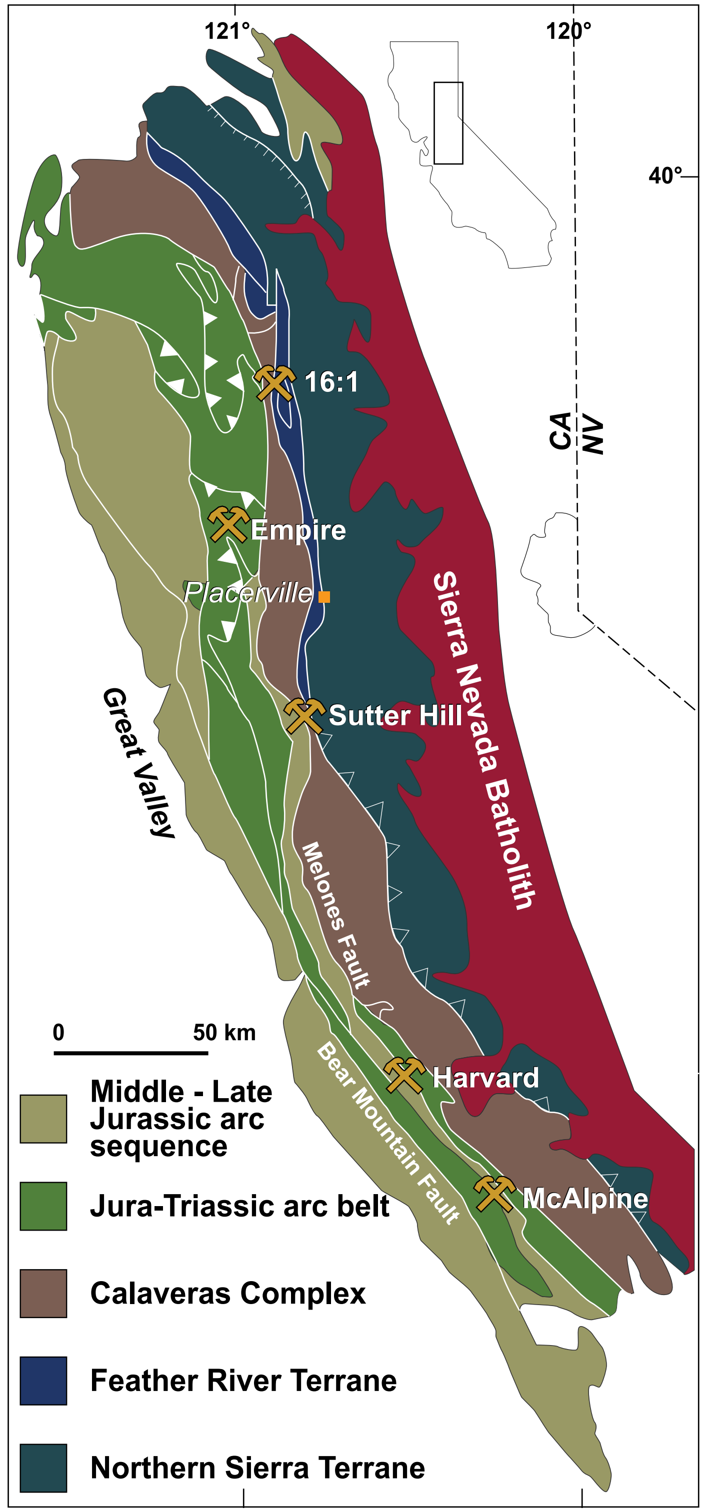


Figure 2. The major deposits of the Sierra Foothills gold province, central California. Most of the lode resource was concentrated along a 200-km-long belt adjacent to the Melones fault system (Mother Lode province) and in the Grass Valley district (i.e, mainly the Idaho-Maryland and Empire deposits). Terranes, after the classification of Snow and Scherer (2006), were accreted to the margin between 272 and 166 Ma. Terrane-bounding faults were characterized by sinistral strike-slip motion from 145-125 Ma, and subsequently by dextral strike-slip. The magmatic arc, the Sierra Nevada batholith, was emplaced from 120-80 Ma along the eastern side of the Northern Sierra terrane.

orogenic gold deposits in the entire orogen, together responsible for about 9 Moz Au recovered. Throughout the foothills province, zones of minimum principal stress and dilation that host the gold ores include conjugate shears, dilational jogs, granitoid pressure shadows, lithologic contacts, and competency contrasts (North, 2006). Proposed ore deposit models range from historically magmatic (Knopf, 1929; Johnston, 1940) to more recently metamorphic (Landefeld, 1988; Jia et al., 2003).

In addition to the lode gold, more than 65 Moz of placer gold has been recovered from Eocene alluvial concentrations, with surprisingly a large amount of this resource having been defined upstream from the known lodes. Additional vein systems eroded during unroofing of the Sierra batholith, a few tens of kilometers landward of the productive lodes, are an obvious possible source for the upstream placers. However, some paleovalleys extended far eastward into Nevada and may define additional source areas for the placer gold (Garside et al., 2005).

The Sierra foothills gold province is underlain by a series of terranes and overlap sequences of Paleozoic to mid-Mesozoic oceanic metasedimentary and metavolcanic rocks (Fig. 2). Classification of these remains argumentative, but most scenarios stress a Triassic-Jurassic growth to the continental margin. The most recent classification by Snow and Scherer (2006) suggests that the North Sierra terrane, comprised of early Paleozoic sedimentary rocks and volcanic arc rocks as young as Middle Jurassic, and that is located immediately seaward of the Sierra batholith, was accreted to the craton margin during a poorly constrained episode sometime between 272 and 166 Ma. It was amalgamated with an outboard mélange, typically termed the Calaveras Complex or terrane, along the Calaveras-Shoo Fly thrust between 235 and 176 Ma. The Jura-Triassic arc belt (includes the Sullivan Creek, Foothills, Don Pedro, Slate Creek, Placerville terranes of various workers), with abundant serpentinite, mélange, and volcanic rocks, hosts most of the gold occurrences. The belt includes a number of steeply-dipping thrust faults (e.g., Melones, Sonora, Bear Valley), traceable for hundreds of kilometers, that are probable boundaries between distinct terranes. This belt was amalgamated with the rocks of the Calaveras Complex between 197 and 177 Ma. Still further west, the Middle-Late Jurassic arc sequence is an overlap assemblage onto the Jura-Triassic arc belt. Finally, the Franciscan melange was added to the convergent margin beginning during Late Jurassic, with the Jura-Cretaceous Great Valley clastic sequence forming between the melange and the Middle-Late Jurassic arc sequence (Blake et al., 2002). The fact that sedimentary deposits in the Great Valley sequence, overlapping rocks of the foothills terranes and Franciscan mélange, are as old as Late Jurassic, indicates that the gold-hosting foothills terranes were being uplifted by Late Jurassic.

Magmatism in the Sierra foothills is concentrated into two episodes, which mainly pre-date and post-date the gold event (see below). Early magmatism is represented by numerous isolated plutons throughout the foothills terranes. These were emplaced mainly between 165 and 140 Ma, and therefore they overlap final collision along the margin and almost certainly final subduction below the terranes of the gold province. Plutons from this episode in the Grass Valley district hosted much of the historic gold resource; the >6 Moz Au Empire deposit is hosted by a Late Jurassic granodiorite. The massive Sierra batholith formed the main magmatic arc tens of kilometers to the east of the older plutons at ca. 120-80 Ma, subsequent to a 20-m.y.-long period with essentially no igneous activity.

Ages of deformation are broadly constrained within the gold province. Throughout the Late Jurassic and earliest Cretaceous many workers report a sinistral oblique convergence along the continental margin (Glazner, 1991; Umhoefer, 2003). This tectonism was responsible for pre-145 Ma thrusting and folding (Schweickert, 2006) and subsequent ca. 145-125 Ma sinistral motion along structures such as the Melones and Bear Mountains fault systems (Sharp, 1988; Umhoefer, 2003); ca. 146-123 Ma regional metamorphism in the foothills (Paterson et al., 1991); and widespread ductile deformation from 151 to 137 Ma, and perhaps to 123 Ma (Saleeby et al., 1989). Much of the deformation overlaps the well-defined magmatic lull. A major change in Farallon-North America convergence established a dextral strike-slip regime within the foothills subsequent to ca. 125 Ma. Glazner (1991) correlated the change in far-field stresses to the onset of batholith emplacement (Fig. 3). Although accretion and subduction were active throughout the Cretaceous in westernmost California, the associated strike-slip faulting was fully concentrated a few hundred kilometers inland within the foothills terranes (Wakabayashi, 1999). The development of the immense Sierra batholith indicates that although this was dominantly a transpressive continental margin, significant Farallon plate underthrusting must also have taken place below the Foothills terranes (Ernst et al., 2008), beginning at approximately the time of gold deposition.

Historically, there have been about twenty dates reported for the gold lodes of the Sierra foothills province (i.e,. Böhlke and Kistler, 1986). The dates range from ca. 144-104 Ma, with the wide scatter reflecting, to a large degree, the K-Ar and Rb-Sr dating methods that inherently possess a large amount of imprecision. In fact, as pointed out by Böhlke and Kistler (1986), the two oldest dates, both from the Brunswick deposit in the Grass Valley district (ca. 144 and 141 Ma), should be interpreted with caution because most of the veins in the district cut granite that is more than 10 m.y. younger than the Brunswick dates. In contrast, Landefeld (1988) argued that the 144-141 Ma dates may be the best approximations for the timing of gold deposition throughout the Sierra foothills because that was the probable period of rising isotherms and metamorphic devolatilization within the host terranes.

Dating of many of the foothills gold deposits during the last year by relatively precise Ar-Ar methods, however, has narrowed the range of vein formation to about 125±10 Ma

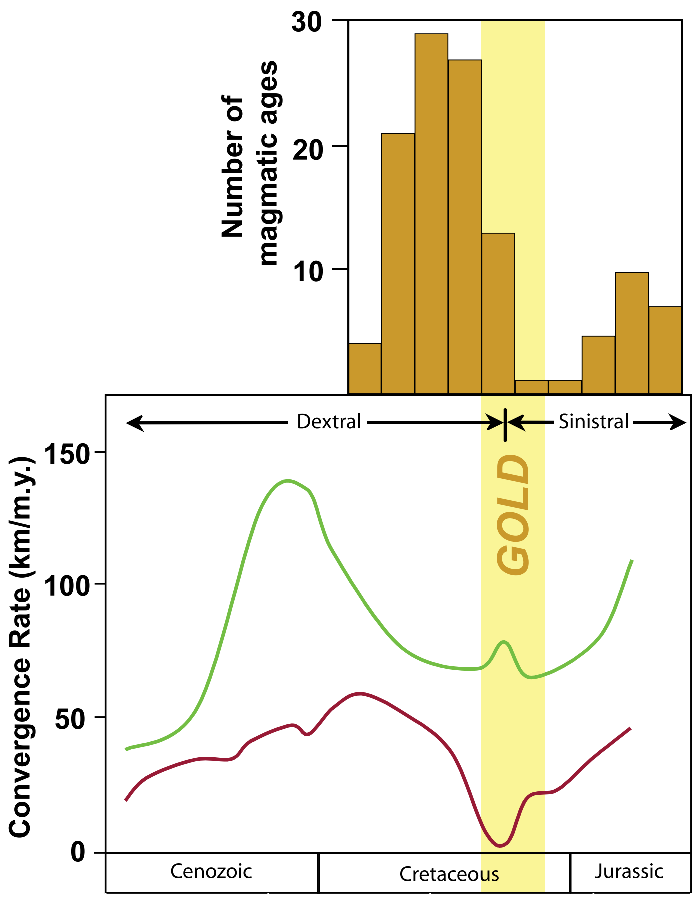


Figure 3. A well-defined 20-m.y.-long magmatic lull during sinistral motion and widespread deformation in the Sierra foothills, then a change to dextral deformation during the onset of arc formation, characterized the Sierra Foothills gold province during Early Cretaceous (from Glazner, 1991). Gold deposition throughout the province (i.e., Marsh et al., 2008) overlaps with this transition in fault kinematics.

(Marsh et al., 2008; Snow et al., 2008). An age of 152.2±1.2 Ma was also obtained by Snow et al. (2008) for hydrothermal mariposite from the Idaho-Maryland orebody in the Grass Valley district, providing further evidence of an older gold event in this one part of the gold province.

The gold deposits in the Sierra foothills post-date all terrane accretion along the continental margin. The majority of the gold deposits were formed about 35 m.y. after the host rocks were added to the edge of the continent. But there is a strong temporal correlation between gold deposition and the change from sinistral to dextral strike-slip on the major fault zones in the terranes of the Jurassic arc sequence (Fig. 3). Goldfarb et al. (2007) suggested this reflects the plume-related plate reconfigurations in the Pacific basin at this time. Such a major change in stresses would lead to significant dilational jogs within the older terrane-bounding fault systems, which would enhance hydrothermal activity particularly during seismic events (e.g., Sibson et al., 1988). The collision of the Guerrero terrane with North America at the latitude of Mexico during this plate reconfiguration may have played a role in the development of the dextral regime (Umhoefer, 2003). For the most part, hydrothermal activity predated by a few million years the emplacement of the oldest plutons of the Sierra batholith, which are exposed about 20-30 km landward of most of the goldfields.

## Juneau gold belt, southeastern Alaska

The deposits of the Juneau gold belt (Fig. 4a) were historically the most significant lode producers in Alaska, with >7 Moz combined production from the giant Alaska-Juneau and Treadwell deposits and significant resources remaining at these deposits and other vein systems along the 160-km-long x 5- to 8-km-wide mineralized zone. The deposits are located within 1-2 km of steeply-dipping, NW-striking thrust faults, which were originally sutures between accreted terranes, and they are about 15-20 km seaward of the main plutons of the Coast batholith (Fig. 4b). Goldfarb et al. (1988a) first suggested a metamorphic model for formation of the orogenic gold deposits, which was well supported by fluid inclusion (Goldfarb et al., 1989) and stable isotope (Goldfarb et al., 1991a) data from deposits throughout the gold belt. The dominantly NW-striking veins occur as temporally overlapping shear and tensional vein systems developed ca. 56-53 Ma, during a shift from a contractional to a transpressional continental margin regime (Miller et al., 1994). The largest gold resources are spatially associated with relatively competent intrusive host rocks scattered along the belt of metasedimentary and metavolcanic terranes, a scenario similar to what was described above for the Grass Valley district in the Sierra foothills.

The gold deposits occur within areas underlain by rocks of the late Paleozoic, parautochthonous Yukon-Tanana terrane, the Permian-Triassic Taku terrane, and the Late Jurassic-Cretaceous Gravina belt (fig. 4b; Gehrels, 2000). The latter represents an overlap basinal assemblage onto the Alexander terrane, located to the west of the gold belt. Yukon-Tanana and Taku terranes are separated by the Sumdum fault and the Taku terrane and Gravina belt by the Fanshaw fault. These steeply east-dipping thrust faults, which each contain gold deposits within both their hangingwall and footwall, were the main sutures during Cretaceous growth of the continental margin. Compressional-related events, such as shearing, folding, magmatism, and metamorphism, are well documented until about ca. 58 Ma (Miller et al., 2000).

Intrusions of a variety of ages are well-dated within the Juneau gold belt. Permian gabbroic bodies, accreted as a part of the Taku terrane, hosted the bulk of the gold ore at the Alaska-Juneau gold deposit. Syn-accretionary, deeply-emplaced diorites of the mid-Cretaceous Admiralty Revilagigedo belt (Brew and Morrell, 1983) include the 105 Ma stock that hosts the Kensington deposit and the 91 Ma sill that hosted the Treadwell gold ores. A 700-km-long belt of 72-58 Ma tonalite

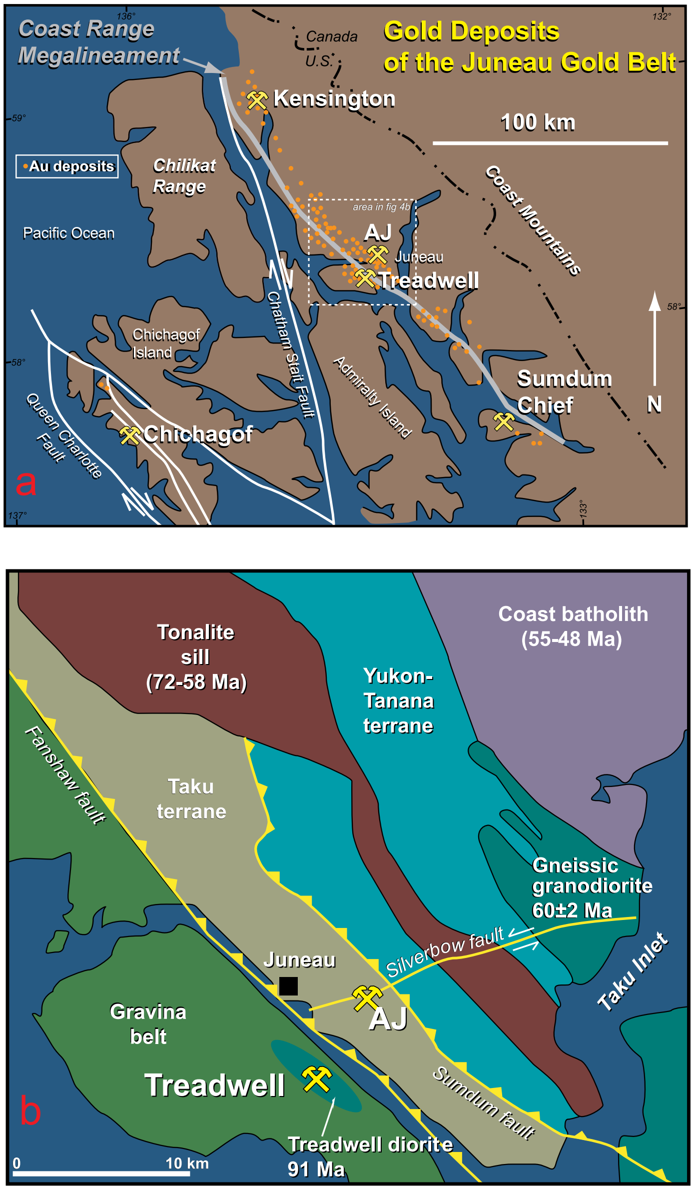


Figure 4. **(a)** The 160-km-long Juneau gold belt, SE Alaska, includes an abundance of deposits (i.e., Kensington, Alaska-Juneau or AJ, Treadwell, and Sumdum Chief) along the length of a complex structural zone, sometimes termed the Coast Range Megalineament, which is overprinted by an inverted Barrovian metamorphic sequence (e.g., Himmelberg et al., 1991). This zone includes two closely-spaced thrust faults (see figure 5) that represent mid-Cretaceous sutures of terranes being added to the Cordilleran orogen (Gehrels, 2000).
**(b)** Central part of the Juneau gold belt in the area of the Alaska-Juneau and Treadwell deposits. The Sumdum and Fanshaw faults separate the Yukon-Tanana and Taku terranes and the Taku terrane and Gravina belt, respectively (Miller et al., 2000). A syndeformational belt of tonalite sills were emplaced 5-10 km landward of most gold deposits between 72 and 58 Ma. Subsequently, post-kinematic plutons of the Coast batholith were emplaced east of the sills and a dextral transpressional regime became widespread throughout the forearc, which may have facilitated movement along the Silverbow fault that offsets the orebodies of the AJ deposit.

sills was emplaced 5-10 km landward of the gold belt (Miller et al., 1994). Simultaneously, between the sills on the east and the most westerly part of the gold belt, an inverted Barrovian metamorphic sequence overprinted the various terranes (e.g., Himmelberg et al., 1991; Stowell and Crawford, 2000). Finally, about 15-20 km east of the gold belt, the majority of the granodioritic and granitic plutons of the Coast batholith crystallized between 55 and 48 Ma.

Compressional deformation fabrics are obvious in the Cretaceous diorites and latest Cretaceous-Paleocene sills, but are not recognized in the Eocene plutons of the Coast batholith. These pre-gold fabrics were defined as D1-D4 by Miller et al. (2000). The D4 event is recognized as a regional shear fabric, termed the Coast Shear Zone, which essentially spatially overlaps and deforms the belt of tonalite sills. Klepeis et al. (1998) noted the variable tectonic history on opposite sides of this shear zone. To the east, the Coast Mountains were rapidly uplifted between ca. 65-57 Ma, whereas to the west and in the terranes that host the Juneau gold belt, mainly reverse movement is recorded as overprinting the Barrovian metamorphism along the thrust faults at 57-55 Ma. This spatial/temporal transition was interpreted as possibly recording a major change in far-field stresses along the continental margin.

The 56-53 Ma gold veins of the Juneau gold belt overprint the 57-55 Ma D4 shear-related deformation. Miller et al (2000) indicate that the non-Andersonian development of the gold-bearing vein systems, such that they are mainly perpendicular to the axis of maximum compression, could reflect a drastic rotation in stress fields at this time. This is consistent with Goldfarb et al. (1991b), who argued that the age of gold mineralization correlates well with the change from a compressional to transpressional continental margin. The initiation of dextral transpression further seaward may have been as old as 63 Ma on the Chatham Strait-Denali fault system (Gehrels, 2000), but may first be recorded in the terranes of the gold belt by features such as the E-W Silverbow fault that offsets the gold orebodies at the Alaska-Juneau deposit.

In summary, gold formation in the Juneau gold belt occurred during a 3-m.y.-long period of fluid flow along the Fanshaw and Sumdum fault systems. These steep faults tapped fluids produced during a Barrovian metamorphic event that was initiated about 15 m.y. earlier. The mineralization event (1) post-dates accretion of the host terranes by at least 35 m.y., (2) overlaps the broadly-defined onset of transpressional movement best recognized along the continental margin to the west, and (3) overlaps the initial stages of massive batholith development to the east, but post-dates 14 m.y. of sill magmatism on the western side of the batholith, which together probably define a single 25-m.y.-long episode of related intrusive activity.

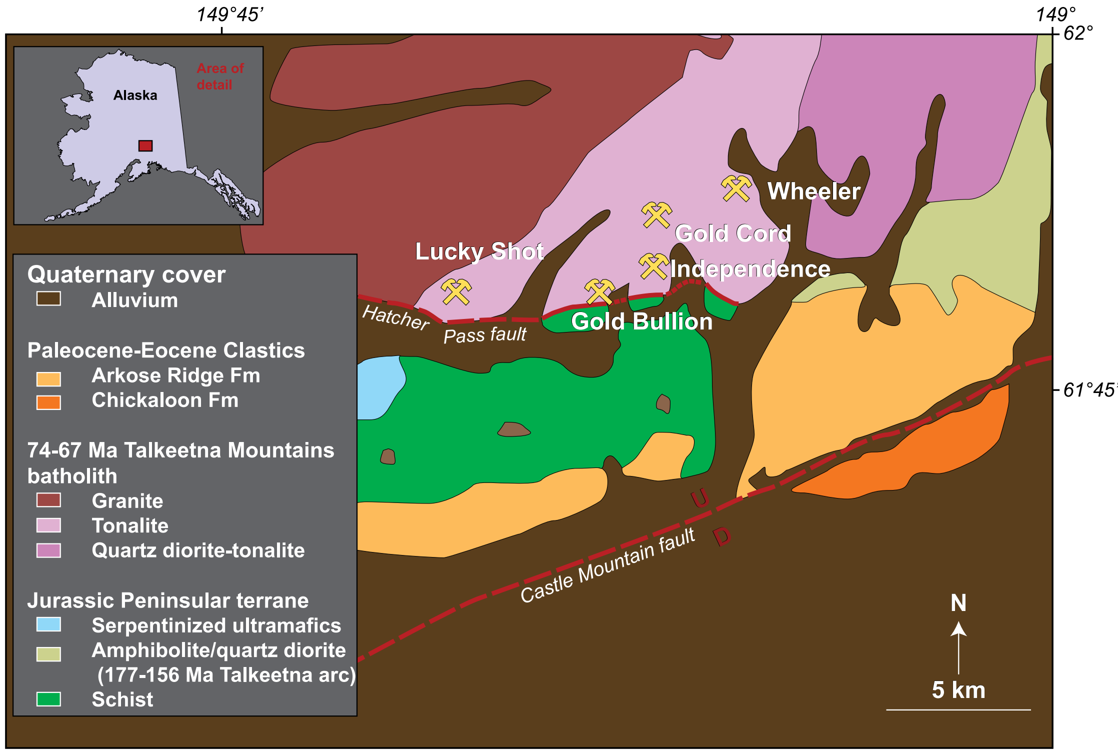


Figure 5. The deposits of the Willow Creek district are localized along the seaward margin of the Talkeetna Mountains batholith, south-central Alaska (Winkler, 1992). Plutons in the southern part of the batholith were emplaced at ca. 74-67 Ma and uplifted between 68 and 61 Ma. The 200-km-long Castle Mountain fault and perhaps the local Hatcher Pass fault zone, probable splays off the regional Border Ranges fault system that is located a few tens of kilometers south of the district, began to show evidence of dextral strike slip by 75-65 Ma.

## Willow Creek district, south-central Alaska

The Willow Creek district (Fig. 5) is the most important gold district in the south-central part of Alaska. It is located along the southern margin of the Talkeetna Mountains batholith. The batholith is a part of the latest Cretaceous-early Tertiary continental margin arc that extends for more than 3000 km, from the Coast batholith in southeastern Alaska, through the Kluane batholith of western Canada, to the Talkeetna Mountains batholith north of Anchorage, and to the Alaska Range (e.g., Moll-Stalcup, 1994). Most of the >600,000 oz of gold production in the Willow Creek district was from the veins of the Independence deposit. A major terrane boundary, the Border Ranges fault system, is located about 30 km south of the gold district, but important splays off that system occur much closer to the gold deposits.

The gold deposits are mainly hosted by latest Cretaceous-earliest Tertiary igneous rocks that have intruded rocks of the Peninsular terrane (Fig. 5). In the region, the Peninsular terrane is dominated by accreted volcanic and intrusive rocks of the Early to Late Jurassic Talkeetna arc (Winkler, 1992). This 1000-km-long oceanic arc was either built upon the Wrangellia-Alexander terrane amalgamation or collided with the amalgamation sometime between Permian and Late Jurassic (Trop and Ridgeway, 2007). In either scenario, the arc was likely accreted to the continental margin by the end of the Jurassic (Clift et al., 2005). Simultaneously, and continuing throughout the Late Cretaceous, mélange and flysch of the Chugach terrane were being accreted to and thrusted below the seaward margin of the Wrangellia-Alexander-Peninsular superterrane along the Border Ranges fault system .

Plutons of the Talkeetna Mountains batholith intruded the southern part of the arc after accretion, but coevally with the latter stages of ongoing subduction/accretion to the south. A number of K-Ar dates from different phases of the batholith are spread between 79-65 Ma; the older half of the range characterizes samples closest to the gold deposits (Winkler, 1992). However, recent U-Pb ages for a number of samples within a few kilometers of some of the gold deposits cluster between 72.5 and 67.3 Ma (Harlan et al., 2003; Dwight Bradley, oral commun., 2004), and are probably the best estimate for the age of the ore host rocks. Regional uplift and exposure of the batholith took place at ca. 68-61 Ma.

The Border Ranges fault system, a few tens of kilometers south of the deposits of the gold district, was reactivated and underwent several hundreds of kilometers of right lateral displacement sometime within the period from latest Cretaceous through Tertiary (Little, 1990; Pavlis and Roeske, 2007). Some of the dextral strike-slip was partitioned onto a 200-km-long northern splay termed the Castle Mountain fault, which is stated to have undergone at least 35 km of slip since 75 Ma (Bunds, 2001) or 130 km of slip post-65 Ma (Pavlis and

Roeske, 2007). The fault is exposed about 5 km south of the gold deposits and the southern margin of the Talkeetna Mountains batholith. More importantly, the smaller and poorly studied Hatcher Pass fault zone is recognized between the batholith margin and schists that are also a part of the Peninsular terrane; gold deposits are within 1-2 km of this fault in mainly the igneous rocks, but also a few small veins are recognized in the schists. Madden-McGuire et al. (1989) defined this fault as a possible "paleotrace" of the Castle Mountain fault. Alternatively, it may just be a low-order fault that has splayed off the Castle Mountain and Border Ranges fault systems.

Argon dating of hydrothermal sericite associated with the gold deposits hosted by the granitoids yielded six ages tightly constrained between 66.9 and 65.6 Ma (Harlan et al., 2003). These dates are 2-3 m.y. younger than argon dates on biotites from the pluton, indicating that the sericite dates are indeed the age of mineralization and not cooling ages. A slightly disturbed profile for white mica from the Thorpe mine, hosted by the schist on the southern side of the Hatcher Pass fault, yielded a weighted average apparent age of 54 Ma. It remains unclear how significant this date may be or whether any significant resource was deposited at this younger time.

Thus, unlike the other Cordillera gold districts, the Willow Creek gold deposits are hosted dominantly within the borders of the continental margin batholith itself and not within the rocks of the accreted terranes adjacent to the arc. The veins formed in the already solidified batholith, as the young intrusions were being uplifted during latest Cretaceous to earliest Paleocene. The intrusions are estimated to have been emplaced no more than about 5 m.y. before they were hydrofractured by the gold-bearing ore fluids. The fluid event is likely coeval with the onset of significant dextral strike-slip motion on splays of the Border Ranges fault system. The deposits themselves formed approximately 80 m.y. after terrane accretion, but northwesterly subduction of younger oceanic crust and overlying sedimentary rocks is likely to have been ongoing during ore formation and, in fact, these underplated rocks are a potential fluid and metals source. If the well-recognized southern Alaska slab window reached as far inland as the Willow Creek district, it would have done so at ca. 62 Ma (Cole et al., 2006), and would have been an unlikely trigger for the 66 Ma gold event.

## Bridge River district, southwestern British Columbia

Bridge River (Fig. 6) is the most important lode gold province in the Canadian part to the North American Cordillera. More than 4 Moz Au was recovered mainly from the Bralorne-Pioneer vein systems from 1897-1971 (Harrop and Sinclair, 1986). These high-grade veins are localized between and along the north-striking Cadwallader and Fergusson thrusts (i.e., the so-called Cadwallader break of Bacon, 1978), which together represent a few kilometers wide zone of complex deformation of Paleozoic volcanic and sedimentary rocks between the Coast batholith to the west and the Bendor pluton to the east. Leitch et al. (1991) suggested that ca. 90 Ma thrusting on these faults was associated with the Bralorne-Pioneer gold deposition. In addition, many other small gold, antimony, and mercury deposits are scattered throughout the district, particularly within a few kilometers of the NNW-trending Castle Pass fault system. Oxygen isotope data for quartz gangue from all these deposits (Maheux, 1989) suggest a consistent fluid signature and thus one main district-wide hydrothermal event. The district is also the most significant Cordilleran gold producer from orogenic gold deposits that are located on the landward side of the continental arc.

The mining district is underlain by a complexly intercalated stratigraphy of rocks of the Cadwallader, Methow, and Bridge River terranes (Fig. 6). Oceanic rocks of the Bridge River terrane are comprised of Mississippian to Middle Jurassic fine-grained clastics, basalts, cherts, mélanges, intrusions, and serpentinites, which were added to the continental margin between late Middle Jurassic and late Early Cretaceous (Rusmore, 1987; Schiarizza et al., 1997). These accretionary prism/oceanic crust rocks were likely amalgamated with the Late Triassic to mid-Cretaceous arc volcanic and clastic rocks of the Cadwallader terrane shortly before accretion. The two terranes were accreted to the Jura-Cretaceous basinal turbidites of the Methow terrane to the east, with the suture being the Yalakom fault on the eastern side of the Bridge River district. In the area of the Bralorne-Pioneer deposit, rocks of the Cadwallader and Bridge River terranes are complexly imbricated along the Cadwalladar and Fergusson thrusts (Schiarizza et al., 1997).

The kinematics of the major, northwest-striking Yalakom fault system and related faults in the Bridge River region were discussed in detail by Umhoefer and Schiarizza (1996). The fault system was a site of contractional deformation until ca. 91-86 Ma, which likely records final Wrangellia collision seaward of the Bridge River and Cadwallader terranes. The main structures in the region were subsequently interpreted to record 30 m.y. of dextral strike-slip as part of an overall transpressional regime, with the first significant slip probably taking place at ca. 69-67 Ma along the Castle Pass splay (Umhoefer and Schiarizza, 1996). The Castle Pass splay is the most westerly part of the Yalakom fault system within the district and is exposed about 5 km east of the Bralorne-Pioneer veins. This dextral slip is interpreted to be a reflection of the change from normal subduction of the Farallon plate to obliquely northward subduction of the Kula plate beginning at ca. 80 Ma along the continental margin (Umhoefer and Miller, 1996).

More local, northeast-dipping, and northwest-striking, mid-Cretaceous thrust faults are mapped in the Bridge River area between the Castle Pass fault and the Coast batholith. These are significant because they host the economically most significant lode deposits of the Bridge River district. The 25-km-long Eldorado fault system records ca. 90 Ma reverse-sinistral movement and likely has a southern continuation that is defined by the Cadwallader fault in the area of the Bralorne-Pioneer veins (Leitch, 1990; Schiarizza et al., 1997). This highly mineralized area is marked by an abrupt change in strike, from

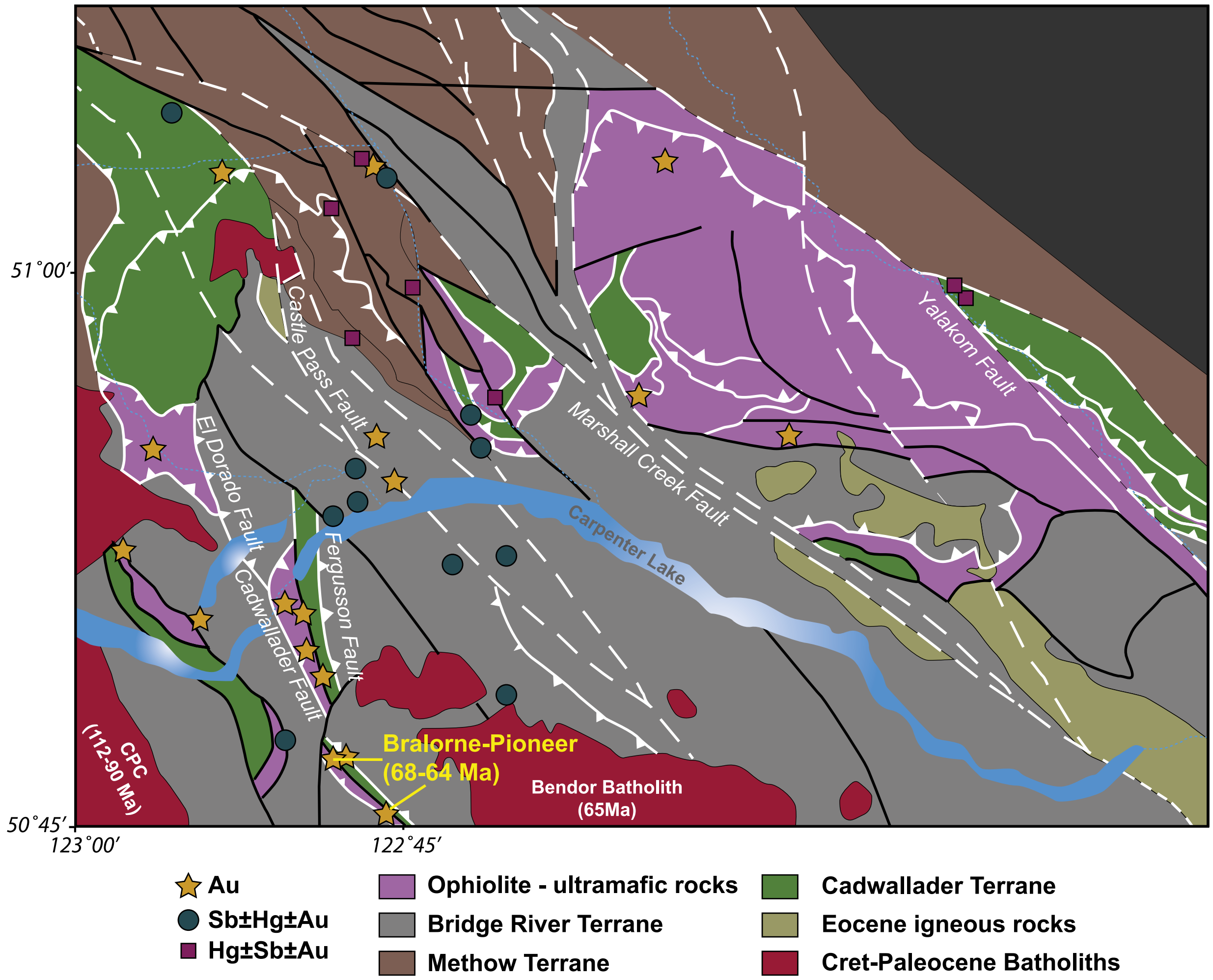


Figure 6. The Bridge River district, containing Hg, Sb, and Au deposits, is located landward of the Coast Plutonic Complex (CPC; or Coast batholith) that forms the Late Cretaceous continental magmatic arc in southern British Columbia. The major gold resource of the Bralorne and Pioneer orebodies is localized between the Cadwallader and Fergusson thrust faults and a few kilometers west of the 65 Ma Bendor stock. The district is underlain by complexly intercalated rocks of the Cadwallader, Methow, and Bridge River terranes, and is cut by a series of NW-striking splays of the Yalakom fault system that likely showed significant dextral strike-slip at ca. 69-67 Ma (Umhoefer and Schiarizza, 1996).

north to northwest, of the local thrust faults (Church, 1996). Other important points stressed by Church (1996) include (1) the recognition of a large dilational zone in the area of mineralization, where the Fergusson fault splays off and then rejoins the Cadwallader thrust and (2) some unspecified and debated amount of lateral motion along the thrust systems.

Igneous bodies of the southeastern part of the Coast batholith border the district to the west and the Bendor pluton outcrops about 3 km east of the Bralorne-Pioneer deposit. The stocks of the batholith in this area are mainly syn- to post-kinematic mid-Cretaceous intrusions that are part of the evolving juvenile Middle Jurassic-Late Cretaceous arc in the northern Cordillera (Friedman et al., 1995). The reported dates of intrusion cluster between 112 and 90 Ma. Latest Cretaceous to early Tertiary igneous rocks outcrop east of the batholith and within the mining district. Many of the dikes and small stocks range in age from about 69-67 Ma and 47-44 Ma, and their emplacement may have been controlled by the dextral strike-slip faulting along the Yalakom fault system (Umhoefer and Schiarizza, 1996). Explacement age of the large Bendor igneous bodies has been uncertain; reported age determinations historically have ranged from 139-56 Ma (Church, 1996).

The mineral deposits of the district are hosted by rocks of both the Cadwallader and Bridge River terranes. The Bralorne-Pioneer ores have been studied in detail by Leitch (1990). The veins are hosted by mainly mafic volcanic rocks at the Pioneer orebody and Permian diorite at Bralorne. Leitch et al. (1991) dated the dikes within the gold-bearing structures and determined a 90 Ma U-Pb age for a pre-ore dike and an 86 Ma K-Ar age for an altered dike interpreted to be syn-ore; thus, a narrow mid-Cretaceous time window was suggested for the gold event, which was also assumed to correlate with thrusting along the Cadwallader break. This 90-86 Ma age was notably older than the estimate of 63.6±1.8 Ma (K-Ar) reported by Pearson (1977) for white mica from the Bralorne host intrusion. Whereas Pearson (1977) assumed the age to date hydrothermal alteration associated with mineralization, Leitch et al. (1991) interpreted it as a product of thermal resetting by Late Cretaceous intrusions. Elsewhere in the district, other K-Ar ages on gold deposits included (1) Harrop and Sinclair's (1986) reported K-Ar dates of hydrothermally altered dikes at the Minto and Congress deposits of 69.4±2.4 and 67.1±1.2, respectively, (2) a date of 57.7±2.0 by Leitch et al. (1991) for sericite from the Gem deposit, and (3) a date of 70±5 Ma for the diorite host rock of the Elizabeth deposit. Combining all the K-Ar data with the Leitch et al. (1991) interpretation for Bralorne-Pioneer, these data suggest distinct middle and Late Cretaceous hydrothermal events in the Bridge River district.

New argon geochronology by Hart et al. (2008), however, indicates that one single ore-forming episode likely characterized the Bridge River district. Dating of hydrothermal micas, from three locations along a 10-km-stretch of the Bralorne-Pioneer veins, are concordant between 68 and 64 Ma, and suggest no earlier mineralizing event. In addition, new U-Pb and Ar-Ar dates for minerals phases from the Bendor stock (Hart et al., 2008) indicate an overlapping age with the mineralization. These results now confirm that (1) gold deposition post-dates accretion of host rocks by perhaps 50 m.y., (2) hydrothermal activity overlaps the initial major dextral strike-slip in the region and post-dates thrusting by at least 20 m.y., (3) hydrothermal activity is at least 20 m.y. younger than final magmatism in the nearby Coast batholith, and (4) both fluid flow and relatively young, coeval magmatic emplacements were probably controlled by the same strike-slip event within the Bridge River district.

## DISCUSSION AND CONCLUSIONS

The tectonic controls of Cordilleran orogenic gold systems received surprisingly limited discussion compared to other mineral deposit types throughout the 1970s and early 1980s, as workers began to place deposit types into their appropriate global tectonic settings. Sawkins (1972) was among the first to point out the correlation between what is now termed "orogenic gold" and subduction-related environments. Mitchell and Garson (1981) identified the distribution of California goldfields within a convergent plate margin setting. But it really wasn't until the late 1980s that the geodynamic settings of orogenic gold deposits of the Cordilleran orogen were thoroughly synthesized.

A series of papers on Cordilleran ore deposits in 1988 described broad tectonic controls of orogenic gold deposits in California (Landefeld, 1988), British Columbia (Nesbitt and Muehlenbachs, 1988) and Alaska (Goldfarb et al, 1988b). Many of the more important consistencies in the orogenic gold model were succinctly discussed by Nesbitt (1991), a few years later, in his summary on Phanerozoic gold in active convergent margins. First-order faults were shown to control the mineralization, particularly those with significant strike-slip components. Gold ores were stressed as forming late during orogeny, subsequent to much of the deformation and metamorphism of the immediate host rocks. Throughout the Cordillera, orogenic gold was now well-recognized as having a broad spatial and temporal link to magmatism, but evidence for a direct genetic link was lacking. A metamorphic model was now the most widely accepted genetic model for these Cordilleran gold systems.

A subsequent summary of orogenic gold deposits of the Pacific rim (Goldfarb et al., 1998) indicated that the largest orebodies may be found outboard, within the margins, or inboard of the continental magmatic arcs, and typically 100-200 km landward of the subduction zone associated with the accreted margin. Arc-related magmatism was stated to have no consistent pattern relative to hydrothermal activity; it may pre-date, be coeval with, or post-date formation of the gold deposits. Available geochronology showed that most Cordilleran gold deposits post-dated regional metamorphism of host rocks by 5-15 m.y. and post-dated accretion/convergence-related deformation by at least 30 m.y. Reconfiguration of plate stresses was hypothesized as critical to ore formation.

During the last decade, an abundance of new data summarized in this paper has further improved our understanding

TABLE 1. TIMING RELATIONSHIPS BETWEEN GOLD DEPOSITION, BATHOLITH FORMATION, AND FAULT MOVEMENTS IN THE NORTH AMERICAN CORDILLERA

| Area | Gold province | Age of mineralization (Ma) | Time post host-rock accretion (m.y.) | Spatial association with batholith | Temporal association with batholith | Tectonic events |
|---|---|---|---|---|---|---|
| Central California | Sierra Foothills (Mother Lode belt, Grass Valley distrcit, Alleghany district) | 150(?), 130-115 | 35 | Seaward | Mainly a few million years pre-batholith | (1) Shift from sinistral to dextral strike slip (2) change in Pacific basin plate motions (3) terrane collision to |
| SW British Columbia | Bridge River (Bralorne-Pioneer lodes) | 68-64 | 50 | Landward | 20 m.y. post-batholith | Onset of dextral strike-slip |
| SE Alaska | Juneau gold belt (Alaska-Juneau, Treadwell, Kensington deposits) | 57-53 | ≥35 | Seaward | End stages of sill emplacement and first stages of batholith | (1) Initiation of transpressive regime (2) shift in Pacific basin plate motions |
| South-central Alaska | Talkeetna Mountains (Willow Creek district) | 67-66 | 80 | Within | 5 m.y. post-batholith | Onset of dextral strike-slip |

of the relationship between orogenic gold ores and orogenesis (Table 1). The formation of major economic goldfields can all be shown to have post-dated accretion of their host rocks by 35-80 m.y. Gold-bearing veins in the Willow Creek and Bridge River districts were formed, respectively, 5 and 20 m.y. subsequent to emplacement of the continental margin magmatic arc. In the Juneau gold belt, the ores post-date initiation of arc magmatism (i.e., the tonalite sill belt) by about 15 m.y., but the main phase of batholith emplacement is syn-ore to 5 m.y. post-ore. In contrast, most of the gold deposits in the California goldfields pre-date, by at least a few million years, the initiation of 40 m.y. of magmatic activity that formed the Sierra Nevada batholith. Thus, whereas continental arcs and gold deposits both may form late during orogenesis, variable controls on melts and fluids are reflected in an inconsistent relative timing between melt migration and fluid flow.

The main control on fluid flow, and thus formation of orogenic gold deposits adjacent to the magmatic arc, is transpressive reactivation of crustal scale faults. Major changes in fault kinematics within the accretionary margin clearly correlate with all large gold-forming events. As was noted by Goldfarb et al (1991b), initiation of transpression in southeastern Alaska was a critical requirement for gold genesis in the Juneau gold belt. A similar geodynamic setting now seems critical for orogenic gold deposit formation throughout the Cordillera. The switch to dextral strike-slip along the terrane-bounding faults of the California foothills, as well as initiation of dextral strike-slip along strands of the Border Ranges fault system in the Willow Creek area of southern Alaska and in the Bridge River region of British Columbia, apparently were essential to ore formation.

This same reactivation of strike-slip faulting characterizes orogenic gold deposit formation worldwide in older Cordilleran-types orogens. Early Cretaceous movement on the Tan-Lu fault in eastern China, simultaneously with Pacific basin plate adjustments that influenced fault reactivations in California, led to deposition of much of China's gold resource (Goldfarb et al., 2007). In the Uralian orogen, the giant mid-Carboniferous gold ores are associated with sinistral strike-slip being initiated during transpressive deformation (Herrington et al., 2005). The Permian orogenic gold deposits of central Asia (i.e., Muruntau, Kumtor; Yakubchuk et al., 2005) correlate with the shift from right-lateral to left-lateral slip, which is recognized to have occurred then throughout the Altaid orogen (e.g., Yin et al., 2005; Briggs et al., 2005). De Ronde and de Wit (1994) identified such changing fault kinematics, from reverse to strike-slip, as critical to formation of orogenic gold deposits back into the Archean. In such transpressional regimes, it is recognized that highest uplift rates with an orogen are concentrated within 10 km of the major, first-order crustal fault zones (Spotila et al., 2007). Therefore, not only would the changing fault dynamics influence hydrothermal fluid migration, but the spatially associated uplift itself is likely to enhance fluid migration and thus metal endowment along the length of this part of an orogen.

## REFERENCES CITED

Bacon, W.R., 1978, Lode gold deposits in western Canada: Canadian Institute of Mining and Metallurgy, Bulletin, v. 71, No. 795, p. 96-104.

Blake, M.C., Graymer, R.W., and Stamski, R.E., 2002, Geologic map and map database of western Sonoma, northernmost Marin, and southernmost Mendocino counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2402, 43 p.

Böhlke, J.K., and Kistler, R.W., 1986, Rb-Sr, K-Ar, and stable isotope evidence for ages and sources of fluid components of gold-bearing quartz veins in the northern Sierra Nevada foothills metamorphic belt, California: Economic Geology, v. 81, p. 296-322.

Brew, D.A., and Morrell, R.P., 1983, Intrusive rocks and plutonic belts of southeastern Alaska, U.S.A., *in* Roddick, J.A., editors, Circum-Pacific plutonic terranes: Geological Society of America Memoir 159, p. 171-194.

Briggs, S.M., Yin, A., Manning, C.E., and Chen, Z.L., 2005, Structural, petrologic, and geochronologic results on the evolution of the Ertix thrust in the south-central Chinese Altai: Geological Society of America Abstracts with Programs, v. 37, n. 7, p. 56.

Bunds, M.P., 2001, Fault strength and transpressional tectonics along the Castle Mountain strike-slip fault, southern Alaska: Geological Society of America Bulletin, v. 113, p. 908-919.

Church, B.N., 1996, Bridge River mining camp geology and mineral deposits: British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1995-3, 159 p.

Clift, P.D., Pavlis, T., DeBari, S.M., Draut, A.E., Rioux, M., and Kelemen, P.B., 2005, Subduction erosion of the Jurassic Talkeetna-Bonanza arc and the Mesozoic accretionary tectonics of western North America: Geology, v. 33, p. 881-884.

Cole, R.B., Nelson, S.W., Layer, P.W., and Oswald, P.J., 2006, Eocene volcanism above a depleted mantle slab window in southern Alaska: Geological Society of America Bulletin, v. 118, p. 140-158.

de Ronde, C.E.J., and de Wit, M.J., 1994, Tectonic history of the Barberton greenstone belt, South Africa--490 million years of Archean crustal evolution: Tectonics, v. 13, p. 983-1005.

Ernst, W.G., Snow, C.A., and Scherer, H.H., 2008, Contrasting early and late Mesozoic petrotectonic evolution of northern California: Geological Society of America Bulletin, v. 120, p. 179-194.

Friedman, R.M., Mahoney, J.B., and Cui, Y., 1995, Magmatic evolution of the southern Coast Belt: constraints from Nd-Sr isotopic systematics and geochronology of the southern Coast Plutonic Complex: Canadian Journal of Earth Sciences, v. 32, p. 1681-1698.

Garside, L.J., Henry, C.D., Faulds, J.E., and Hinz, N.H., 2005, The upper reaches of the Sierra Nevada auriferous gold channels, California and Nevada, *in* Rhodes, N.H., Steininger, R.C., and Vikre, P.G., eds., Windows to the World, Reno: Geological Society of Nevada Symposium Proceedings Volume, p. 209-235.

Gehrels, G.E., 2000, Geology and U-Pb geochronology of the western flank of the Coast Mountains between Juneau and Skagway, southeastern Alaska, *in* Stowell, H.H., and McClelland, W.C., eds., Tectonics of the Coast Mountains, southeastern Alaska and British Columbia: Geological Society of America Special Paper 343, p. 213-234

Glazner, A.F., 1991, Plutonism, oblique subduction, and continental growth: An example from the Mesozoic of California: Geology, v. 19, p. 784-786.

Goldfarb, R.J, Baker, T., Dube, B., Groves, D.I., Hart, C.J.R., and Gosselin, P., 2005, Distribution, character and genesis of gold deposits in metamorphic terranes: Economic Geology, 100th Anniversary Volume, p. 407-450.

Goldfarb, R.J., Groves, D.I., and Gardoll, S., 2001, Orogenic gold and geologic time; a global synthesis: Ore Geology Reviews, v. 18, p. 1-75.

Goldfarb, R.J., Hart, C.J.R., Davis, G., and Groves, D.I., 2007, East Asian gold - Deciphering the anomaly of Phanerozoic gold in Precambrian cratons: Economic Geology, v. 102, p. 341-346.

Goldfarb, R.J., Leach, D.L., and Pickthorn, W.J., 1988b, Accretionary tectonics, fluid migration, and gold genesis in the Pacific Border Ranges and Coast Mountains, southern Alaska, *in* Kusvarsanyi, A., and Grant, S. K., eds., North American Conference on tectonic control of ore deposits and vertical and horizontal extent of ore systems: University of Missouri - Rolla, Special Publication, p. 67-79.

Goldfarb, R. J., Leach, D. L., Pickthorn, W. J., and Paterson, C. J., 1988a, Origin of lode-gold deposits of the Juneau gold belt, southeastern Alaska: Geology, v. 16, p. 440-443.

Goldfarb, R.J., Leach, D.L., Rose, S.C., and Landis, G.P., 1989, Fluid inclusion geochemistry of gold-bearing quartz veins of the Juneau gold belt, southeastern Alaska: Implications for ore genesis: Economic Geology Monograph 6, p. 363-375.

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.

Goldfarb, R. J., Newberry, R. J., Pickthorn, W. J., and Gent, C. A., 1991a, Oxygen, hydrogen, and sulfur isotope studies in the Juneau gold belt, southeastern Alaska--constraints on the origin of hydrothermal fluids: Economic Geology, v. 86, p. 66-80.

Goldfarb, R.J., Phillips, G.N., and Nokleberg, W.J., 1998, Tectonic setting of synorogenic gold deposits of the Pacific Rim: Ore Geology Reviews, v. 13, p. 185-218.

Goldfarb, R.J., Snee, L.W., Miller, L.D., and Newberry, R.J., 1991b, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: Nature, v. 354, p. 296-299

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., and Robert, F., 1998, Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types: Ore Geology Reviews, v. 13, p. 7-27.

Groves, D.I., Goldfarb, R.J., Robert, F., and Hart, C.J.R., 2003, Gold deposits in metamorphic belts: overview of current understanding, outstanding problems, future research, and exploration significance: Economic Geology, v. 98, p. 1-29.

Harlan, S.S., Snee, L.W., Vielreicher, R.M., Goldfarb, R.J., and Mortensen, J., and Bradley, D.C., 2003, Age and cooling history of gold deposits in the Willow Creek mining district, Talkeetna Mountains, south-central Alaska: Geological Society of America Abstracts with Programs, v. 35, p. 235.

Harrop, J.C. and Sinclair, A.J., 1986, A re-evaluation of production data, Bridge River Bralorne Camp (92J): Geological Fieldwork, 1985, British Columbia Ministry of Energy, Mines and Petroleum Resources, p. 303-310.

Hart, C.J.R., Goldfarb, R.J., Ullrich, T.D., and Friedman, R., 2008, Gold, granites, and geochronology: Timing of formation of the Bralorne-Pioneer gold orebodies and the Bendor batholith: British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 2008-1, p. 47-54.

Herrington, R.J., Zaykov, V.V., Maslennikov, V.V., Brown, D., and Puchkov, V.N., 2005, Mineral deposits of the Urals and links to geodynamic evolution: Economic Geology, 100$^{th}$ Anniversary Volume, p. 1069-1098.

Himmelberg, G.R., Brew, D.A. and Ford, A.B., 1991, Development of inverted metamorphic isograds in the western metamorphic belt, Juneau, Alaska: Journal of Metamorphic Geology, 9: p. 165-180.

Jia, Y., Kerrich, R., and Goldfarb, R.J., 2003, Metamorphic origin of ore-forming fluids for orogenic gold-bearing quartz vein systems in the North American Cordillera: Constraints from a reconnaissance study of $\delta^{15}$N, $\delta$D, and $\delta^{18}$O: Economic Geology, v. 98, p. 109-123.

Johnston, W.D., 1940, The gold-quartz veins of Grass Valley, California: U.S. Geological Survey Professional Paper 194, 101 p.

Kerrich, R., Goldfarb, R. J., Groves, D. I., and Garwin, S., 2000, The geodynamics of world-class gold deposits: characteristics, space-time distribution, and origins: Reviews in Economic Geology, v. 13, p. 501-551.

Klepeis, K.A., Crawford, M.L., and Gehrels, G.E., 1998, Structural history of the crustal-scale Coast shear zone near Portland Inlet, SE Alaska and British Columbia: Journal of Structural Geology, v. 20, p. 883-904.

Knopf, A., 1929, The Mother Lode system of California: U.S. Geological Survey Professional Paper 157, 88 p.

Landefeld, L.A., 1988, The geology of the Mother Lode gold belt, Sierra Nevada Foothills Metamorphic Belt, California, *in* Kusvarsanyi, A., and Grant, S. K., eds., North American Conference on tectonic control of ore deposits and vertical and horizontal extent of ore systems: University of Missouri - Rolla, Special Publication, p. 47-56.

Leahy, K., Barnicoat, A.C., Foster, R.P., Lawrence, S.R., and Napier, R.W., 2005, Geodynamic processes that control the global distribution of giant gold deposits, *in* McDonald, I., Boyce, A.J., Butler, I.B., Herrington, R.J., and Polya, D.A., eds., Mineral deposits and Earth evolution: Geological Society Special Publication 248, p. 119-132.

Leitch, C.H.B., 1990, Bralorne: A mesothermal, shield-type vein gold deposit of Cretaceous age in southwestern British Columbia: Canadian Institute of Mining, Metallurgy, and Petroleum Bulletin, v. 83, n. 941, p. 53-80.

Leitch, C.H.B., van der Heyden, P., Godwin, C.I., Armstrong, R.L., and Harakal, J.E., 1991, Geochronometry of the Bridge River Camp, southwestern British Columbia: Canadian Journal of Earth Science, v. 28, p. 195-208.

Little, T.A., 1990, Kinematics of wrench and divergent-wrench deformation along a central part of the Border Ranges fault system, northern Chugach Mountains, Alaska: Tectonics, v. 9, p. 585-611.

Madden-McGuire, D.J., Silberman, M.L. and Church, S.E., 1989, Geologic relationships, K-Ar ages, and isotopic data from the Willow Creek gold mining district, southern Alaska: Economic Geology Monograph 6, p. 242-251.

Maheux, P.J., 1989, A fluid inclusion and light stable isotope study of antimony-associated gold mineralization in the Bridge River District, British Columbia, Canada: Edmonton, University of Alberta, M.Sc. Thesis, 160 p.

Marsh E.E., Goldfarb, R.J., Groves, D.I., Bierlein, F.P., Kunk, M.J., and Creaser, R.A., 2008, New constraints on the timing of gold formation in the Sierra foothills province, central California, *in* Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 369-388.

McCoy, D., Newberry, R.J., Layer, P.W., DiMarchi, J.J., Bakke, A.A., Masterman, J.S., and Minehane, D.L., 1997, Plutonic-related gold deposits of interior Alaska: Economic Geology Monograph 9, p. 191-241.

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. 203-207.

Miller, L.D., Stowell, H.H., and Gehrels, G.E., 2000, Progressive deformation associated with mid-Cretaceous to Tertiary contractional tectonism in the Juneau gold belt, Coast Mountains, southeastern Alaska, *in* H.H. Stowell and W.C. McClelland, eds., Tectonics of the Coast Mountains, southeastern Alaska and British Columbia: Geological Society of America Special Paper 343, p. 193-212.

Mitchell, A.H.G., and Garson, M.S., 1981, Mineral deposits and global tectonic settings: Academic Press, 405 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: Geological Society of America, The Geology of North America, v. G-1, p. 589-620.

Nesbitt, B.E., 1991, Phanerozoic gold deposits in tectonically active continental margins, *in* Foster, R.P., ed., Gold metallogeny and exploration: London, Blackie, p. 63-103.

Nesbitt, B.E., and Muehlenbachs, K., 1988, Genetic implications of the association of mesothermal gold deposits with major strike-slip fault systems, *in* Kusvarsanyi, A., and Grant, S. K., eds., North American Conference on tectonic control of ore deposits and vertical and horizontal extent of ore systems: University of Missouri - Rolla, Special Publication, p. 57-66.

North, H., 2006, Controls on orogenic gold mineralization in the Mother Lode gold province, California: Perth, University of Western Australia, Earth Science Honours Thesis, 105 p.

Oldow, J.S., Bally, A.W., Ave Lallemant, H.G., and Leaeman, W.P., 1989, Phanerozoic evolution of the North American Cordillera, United States and Canada, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America - An overview: Boulder, Colorado, Geological Society of America, The Geology of North America, v. A, p. 139-232.

Paterson, S.R., Tobisch, O.T., and Vernon, R.H., 1991, Emplacement and deformation of granitoids during volcanic arc construction in the Foothills terrane, central Sierra Nevada, California: Tectonophysics, v. 191, p. 89-110.

Pavlis, T.L., and Roeske, S.M., 2007, The Border Ranges fault system, southern Alaska, *in* Ridgway, K.D., Trop, J.M., Glen, J.M.G., and O'Neil, J.M., eds., Tectonic growth of a collisional continental margin - crustal evolution of southern Alaska: Geological Society of America Special Paper 431, p. 95-128.

Pearson, D.E., 1977, Mineralization in the Bridge River Camp: British Columbia Ministry of Energy, Mines and Petroleum Resources, Geology in British Columbia, p. G57-G63.

Rusmore, M.E., 1987, Geology of the Cadwallader Group and the Intermontane-Insular superterrane boundary, southwestern British Columbia: Canadian Journal of Earth Sciences, v. 24, p. 2279-2291.

Saleeby, J.B., Geary, E.E., Paterson, S.R., and Tobisch, O.T., 1989, Isotopic systematics of Pb/U (zircon) and $^{40}Ar/^{39}Ar$ (biotite-hornblende) from rocks of the central Foothills terrane, Sierra Nevada, California: Geological Society of America Bulletin, v. 101, p. 1481-1492.

Sawkins, F.J., 1972, Sulfide ore deposits in relation to plate tectonics: Journal of Geology, v. 80, p. 377-397.

Schiarizza, P., Gaba, R.G., Glover, J.K., Garver, J.I., and Umhoefer, P.J., 1997, Geology and mineral occurrences of the Taseko - Bridge River area: British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 100, 291 p.

Schweickert, R.A., 2006, Accretionary tectonics of the southern part of the western Sierra Nevada metamorphic belt: University of Nevada-Reno, Field Trip Guide, 48 p.

Sharp, W.D., 1988, Pre-Cretaceous crustal evolution in the Sierra Nevada region, California, *in* Ernst, W.G., ed., Metamorphism and crustal evolution, conterminous United States (Rubey volume 7): Englewood Cliffs, New Jersey, Prentice Hall, p. 824-864.

Sibson, R.H., Robert, F., and Poulsen, K.H., 1988, High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits: Geology, v. 16, p. 551-555.

Snow, C.A., Bird, D.K., Metcalf, J., and McWilliams, M., 2008, Chronology of gold mineralization in the Sierra Nevada foothills from $^{40}Ar/^{39}Ar$ dating of mariposite: International Geology Review, v. 50, p. 503-518.

Snow, C.A., and Scherer, 2006, Terranes of the western Sierra Nevada foothills metamorphic belt, California: A critical review: International Geology Review, v. 18, p. 46-62.

Spotila, J.A., Niemi, N., Brady, R., House, M., Buscher, J., and Oskin, M., 2007, Long-term continental deformation associated with transpressive plate motion: The San Andreas fault: Geology v. 35, p. 967-970.

Stowell, H.H., and Crawford, M.L., 2000, Metamorphic history of the Coast Mounatins orogen, western British Columbia and southeastern Alaska, *in* Stowell, H.H., and McClelland, W.C., eds., Tectonics of the Coast Mountains, southeastern Alaska and British Columbia: Geological Society of America Special Paper 343, p. 257-284.

Stuwe, K., 1998, Tectonic constraints on the timing relationships of metamorphism, fluid production and gold-bearing quartz vein emplacement: Ore Geology Reviews, v. 13, p. 219-228.

Trop, J.M., and Ridgway, K.D., 2007, Mesozoic and Cenozoic tectonic growth of southern Alaska - A sedimentary basin perspective, *in* Ridgway, K.D., Trop, J.M., Glen, J.M.G., and O'Neil, J.M., eds., Tectonic growth of a collisional continental margin - crustal evolution of southern Alaska: Geological Society of America Special Paper 431, p. 55-94.

Umhoefer, P.J., 2003, A model for the North America Cordillera in the Early Cretaceous: Tectonic escape related to arc collision of the Guerrero terrane and a change in North America plate motion, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.I., and Martin-Barajas, A., eds., Tectonic evolution of northwestern Mexico and southwestern USA: Geological Society of America Special Paper 374, p. 117-134.

Umhoefer, P.J., and Miller, R.B., 1996, Mid-Cretaceous thrusting in the southern Coast Belt, British Columbia and Washington, after strike-slip fault reconstruction: Tectonics, v. 15, p. 545-565.

Umhoefer, P.J. and Schiarizza, P., 1996, Latest Cretaceous to early Tertiary dextral strike-slip faulting on the southeastern Yalakom fault system, southeastern Coast Belt, British Columbia: Geological Society of America Bulletin, v.108, p. 768-785.

Wakabayashi, J., 1999, Subduction and the rock record - Concepts developed in the Franciscan Complex, California, *in* Moores, E.M., Sloan, D., and Stout, D.L., eds., Classic Cordilleran concepts - A view from California: Geological Society of America Special Paper 338, p. 123-133

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

Yakubchuk, A.S., Shatov, V.V., Kirwin, D., Edwards, A., Tomurtogoo, O., Badarch, G., and Buryak, V.A., 2005, Gold and base metal metallogeny of the central Asian orogenic supercollage: Economic Geology, 100th Anniversary Volume, p. 1035-1068.

Yin, A., Briggs, S.M., Manning, C.E., Kelty, T.K., Chen, Z.L., and Dash, B., 2005, Making sense of CAOS - preliminary results from an integrated geologic investigation of the Central Asian Orogenic System (=Altaids): Geological Society of America Abstracts with Programs, v. 37, n. 7, p. 56.