Link between ridge subduction and gold mineralization in southern Alaska

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ABSTRACT

$^{40}Ar/^{39}Ar$ geochronology reveals that turbidite-hosted gold deposits in the southern Alaska accretionary prism are the same age as nearby near-trench plutons. These early Tertiary plutons and gold lodes formed above a slab window during subduction of an oceanic spreading center. Ridge subduction is a previously unrecognized tectonic process for the generation of lode gold.

INTRODUCTION

Turbidite-hosted lode-gold deposits in the Kenai and Chugach mountains of southern Alaska have an unusual tectonic setting—they lie within a vast accretionary complex (Fig. 1). Fore-arc areas are notable for their low heat flow, and thus hydrothermal fluid circulation and gold mineralization are not expected or usually found in such a setting.

The tectonic setting of Mesozoic and older gold deposits is generally equivocal, in large part due to complex post-ore formation deformation and uncertainties in the global plate mosaic. Tertiary deposits are more promising for the study of tectonic events that trigger ore formation because marine-based plate reconstructions and high-resolution geochronology provide a relatively good record of the tectonic setting. In this paper we present new geochronological evidence linking formation of early Tertiary turbidite-hosted gold deposits in the southern Alaska accretionary prism with an episode of ridge subduction (i.e., subduction of an oceanic spreading center beneath a convergent plate boundary).

GOLD IN THE SOUTHERN ALASKA ACCRETIONARY PRISM

The Mesozoic and early Tertiary accretionary prism of Alaska extends from Sanak Island in the southwest to Baranof Island in the southeast (Fig. 1). The prism has been subdivided into subparallel belts. The farthest-landward belt (McHugh Complex and correlative units) is a melange with rocks that range in age from Triassic to Cretaceous. Successively younger belts of mostly turbidites and slate lie farther outboard. These include the Campanian and Maastrichtian Valdez Group and its correlatives, and farther seaward, the Paleocene and Eocene Orca Group. Overall, the belts young in a seaward direction, suggesting they were progressively accreted at a long-lived convergent margin (Plafker et al., 1994). Following accretion of the Valdez Group and the more landward part of the Orca Group, the subduction complex was intruded by a suite of near-trench plutons—the Sanak-Baranof belt of Hudson et al. (1979) (Fig. 1). Near-trench magmatism was followed by renewed subduction and accretion.

There are widespread gold veins in the Valdez Group and its correlatives, and the Orca Group and McHugh Complex also have a small number of gold occurrences. Gold and near-trench intrusions are both found along much of the length of the accretionary prism, but there is no consistent spatial relation between gold mineralization and intrusions (Haeussler and Bradley, 1993). Although some gold-quartz veins cut

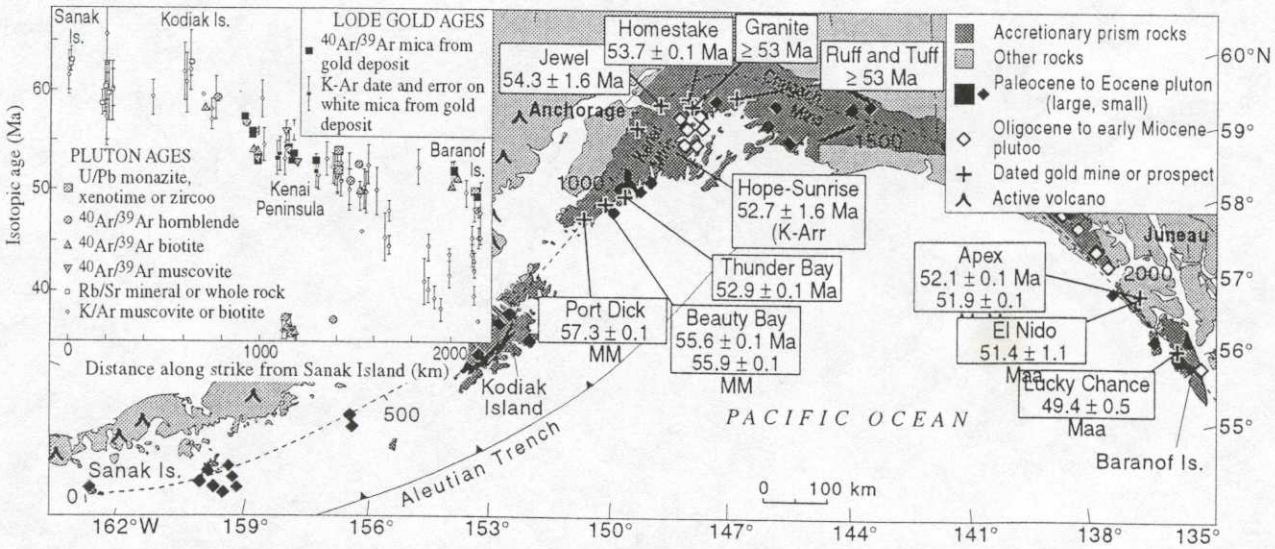

Figure 1. Map of southern Alaska showing accretionary prism, plutons of Sanak-Baranof belt, modern volcanoes, and $^{40}Ar/^{39}Ar$ isotopic ages of gold-quartz veins. Numbers along dashed reference line show distance in kilometres from southern tip of Sanak Island to Baranof Island. Inset: Plot of isotopic ages of gold occurrences and intrusions vs. distance along strike around Sanak-Baranof belt. Error bars on $^{40}Ar/^{39}Ar$ and U/Pb ages are too small to be shown on plot. Few conventional K-Ar intrusion ages show evidence of excess argon (see Bradley et al., 1993), and are not shown. Data are from Bradley et al. (1993), Taylor et al. (1994), Poole and Wright (1995, personal commun.), and this study.

Data Repository item 9549 contains additional material related to this article.

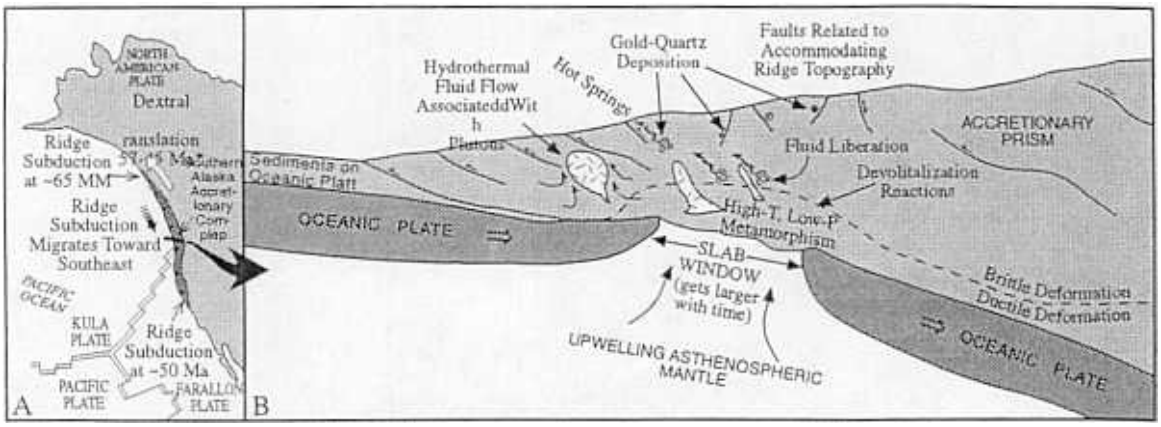

Figure 2. A: Plate-tectonic setting of gold mineralization during ridge subduction in southern Alaska accretionary prism. Kula-Farallon ridge location is constrained by ages of near-trench intrusions (Bradley et al., 1993). Asterisk refers to northward translation of accretionary prism inferred by paleomagnetic data. See Bol et al. (1992) for discussion. B: Schematic cross section across accretionary prism showing processes involved during ridge subduction and gold mineralization. Cross section assumes ridge is at high angle to trench.

veins are similar to those from veins typical of medium-grade metamorphic environments throughout the world. The consistency of these data led Goldfarb et al. (1986) to propose that the mineralizing fluids were a product of regional metamorphism which affected rocks beneath the level of current exposure.

EARLY TERTIARY RIDGE SUBDUCTION IN SOUTHERN ALASKA

A fundamental feature of plate reconstructions for the North Pacific basin in early Tertiary time is subduction of the Kula-Farallon spreading ridge beneath North America (Atwater, 1989). In these reconstructions, the position of the trench-ridge-trench triple junction of the Kula, Farallon, and North American plates has been conjectural.

The Sanak-Baranof belt of near-trench plutons provides strong evidence for the former location of a triple junction in southern Alaska (Bradley et al., 1993; Sisson and Pavlis, 1993). Petrogenetic, isotopic, and geochemical studies of the granodiorite, granite, and tonalite plutons indicate that basaltic underplating led to melting of the flysch (Hudson et al., 1979; Hill et al., 1981; Barker et al., 1992; Harris et al., 1992). The plutons intruded strata within a few million years of their incorporation into the accretionary complex, while a magmatic arc was active a few hundred kilometres landward (Plafker et al., 1994).

Near-trench magmatism is the hallmark of ridge subduction (Sisson et al., 1994). In the Solomon Sea where the Woodlark spreading center is being subducted beneath the New Britain arc, submarine volcanoes dot the fore arc and even the trench floor (Taylor and Exon, 1987). Similarly, where the Nazca-Antarctic ridge is being subducted at the Chile Trench, Pliocene near-trench plutons and hot springs occur more than 100 km seaward of the magmatic arc (Forsythe et al., 1986).

In southern Alaska, a plot of intrusion age vs. position along strike shows that near-trench magmatism progressed from about 66–63 Ma in the west to about 50 Ma in the east (Fig. 1; see also Bradley et al., 1993). The age progression along the accretionary prism suggests migration of a trench-ridge-trench triple junction; it cannot be explained by other models for magmatism such as spontaneous melting of accreted flysch or subduction of a hot spot.

GEOCHRONOLOGY

To better determine the timing of gold mineralization with respect to numerous dated near-trench intrusions (Bradley et al., 1993; Fig. 1), we obtained 12 $^{40}Ar/^{39}Ar$ dates on micas at lode-gold occurrences, and four $^{40}Ar/^{39}Ar$ dates on micas from host or nearby intrusions (Table 1, and table and diagrams[1]). We used analytical methods described in Snee et al. (1988) and in GSA Data Repository item 95XX.[1] Three K-Ar dates (Silberman et al., 1981; Winkler et al., 1981) and five of our $^{40}Ar/^{39}Ar$ dates without data have previously been reported for the gold deposits (Borden et al., 1992; Taylor et al., 1994); near-trench intrusion ages are summarized in Figure 1 and in Bradley et al. (1993).

Half of our samples from gold occurrences have well-defined plateaus; these analyses had good radiogenic yields, and $^{39}Ar/^{37}Ar$ ratios consistent with derivation from white mica. In these cases, we interpret the plateau age as the age of mineralization (Table 1 and Fig. 1). The other samples suffered from one or more of the following: contamination with another mineral phase, small size, and/or low radiogenic yield, but valid approximations of the ages of these gold occurrences could still be made.

The dated gold occurrences define a trend of older to the west and younger to the east (Fig. 1 and Table 1). Despite some scatter the dated gold occurrences follow the same eastward-younging age progression as crystallization and nearly identical cooling ages on large and small near-trench plutons. Therefore, we propose that gold mineralization in southern Alaska was a consequence of ridge subduction.

MODEL FOR RIDGE-SUBDUCTION–RELATED GOLD DEPOSITS IN SOUTHERN ALASKA

A fundamental requirement for generating a lode-gold deposit is a heat source. The heat source must be large enough to mobilize fluids that will scavenge gold from suitable source rocks and later deposit the gold in lodes at appropriate pressure (P) and temperature (T) conditions. Ridge subduction and processes associated with heat transport in this tectonic setting are favorable for gold mineralization.

During ridge subduction, a slab window opens—an area in which relatively hot asthenospheric mantle is in contact with the base of the cold and wet accretionary prism (Fig. 2). In southern Alaska, the resulting thermal anomaly caused (1) localized high-T, low-P metamorphism (Hudson, 1982; Sisson et al., 1989), and (2) partial melting of accreted sediments leading to intrusion of granitoids (Hudson et al., 1979) (Fig. 2). Metamorphism of sediments to amphibolite facies (Sisson et al., 1989) involved desulfidization reactions, which we suggest added gold-complexing sulfur species to the evolving H_2O-CO_2 fluids. The liberated gold-

[1]GSA Data Repository item 9549, $^{40}Ar/^{39}Ar$ data and Ar release spectra diagrams, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

TABLE 1. AGES OF GOLD MINERALIZATION IN THE ACCRETIONARY PRISM IN SOUTHERN AND SOUTHEASTERN ALASKA

Name of gold mine or prospect	Distance from Sanak Island*	Date and error (Ma ± 1 σ	Dating method	Mineral dated	Source	Vein host rocks/Comments on dating
Emplacement ages of gold mines and prospects						
Port Dick prospect	920	57.3 ± 0.1	$^{40}Ar/^{39}Ar$	white mica	This study	Felsic dike in McHugh Complex; small sample (10.6 mg), date based on single step of analysis with 67.8% of ^{39}Ar released, and radiogenic yield of 86.6%.
Beauty Bay mine	960	55.6 ± 0.1	$^{40}Ar/^{39}Ar$	clear mica	This study†	Valdez Group rocks; plateau date, $^{39}Ar/^{37}Ar$ ratios (96-474) consistent with white mica, good radiogenic yields.
Beauty Bay mine	960	55.9 ± 0.1	$^{40}Ar/^{39}Ar$	gold-colored mica	This study†	Valdez Group rocks; preferred date is based on the average of the two steps with the highest radiogenic yield (95.8% and 94.9%) which comprises 37.2% of the ^{39}Ar released.
Thunder Bay gold occurrence	990	52.9 ± 0.1	$^{40}Ar/^{39}Ar$	white mica	This study	Polymetallic gold-sulfide vein that cuts a granitic intrusion in Valdez Group; good radiogenic yields, very flat plateau.
Kenai Star mine	1090	52.7 ± 1.6	K-Ar	whole rock	Silberman et al., 1981	Hydrothermally altered, mineralized felsic dike that cuts the Valdez Group.
Kenai Star mine	1105		K-Ar	musco-vite	Silberman et al., 1981	Felsic dike with mineralized quartz vein that cuts the Valdez Group.
Jewel mine	1150	54.3 ± 0.1	$^{40}Ar/^{39}Ar$	white mica	This study	Valdez Group rocks; plateau date, $^{39}Ar/^{37}Ar$ ratios (149-1902) consistent with white mica, good radiogenic yields.
Granite mine	1170		$^{40}Ar/^{39}Ar$	white mica	This study	Hydrothermally altered granite that cuts Valdez Group; ~30% of mica was light green (chl?), argon loss spectrum, no plateau, age probably older than the age of the oldest step with high $^{39}Ar/^{37}Ar$.
Homestake mine	1190	53.7 ± 0.1	$^{40}Ar/^{39}Ar$	white mica	This study	Hydrothermally altered granite that cuts Valdez Group; plateau date, high radiogenic yields, minor apparent argon loss, possibly due to observed plagioclase contamination of mineral separate.
Ruff and Tuff mine	1290		$^{40}Ar/^{39}Ar$	white mica	This study	Hydrothermally altered granite that cuts the Valdez Group; argon loss spectrum suggests that age is probably older than the age of the oldest step with a high $^{39}Ar/^{37}Ar$ (=155).
Ruff and Tuff mine			K-Ar		Winkler et al., 1981	From Ruff and Tuff, not Gold King prospect as originally reported.
El Nido mine	2010		$^{40}Ar/^{39}Ar$	sericite	This study‡	Cretaceous dioritic pluton; humped spectra date is total-gas date with large assigned error, to reflect low confidence in analysis.
	2010	52.1 ± 0.	$^{40}Ar/^{39}Ar$	musco-vite	This study	Cretaceous dioritic pluton; plateau date, $^{39}Ar/^{37}Ar$ ratios (>298) consistent with white mica, good radiogenic yields.
Apex mine			$^{40}Ar/^{39}Ar$		This study	Cretaceous dioritic pluton; plateau date, good radiogenic yields.
Lucky Chance mine		49.4 ± 0.5	$^{40}Ar/^{39}Ar$	white mica	This study	Sitka Graywacke; small sample (5 mg), date based on single step of analysis with 95.1% of ^{39}Ar released, and poor radiogenic yield of 45.5%.
Cooling ages of intrusions near gold mineral occurrences						
Thunder Bay Granitic sill	990	53.7 ± 0.1	$^{40}Ar/^{39}Ar$	biotite	This study	Plateau date, good radiogenic yields, slightly disturbed spectrum indicating some chlorite contamination, but date is about the same as an isochron or a total gas date.
Granite at Granite mine	1170	56 ±	$^{40}Ar/^{39}Ar$		This study	Disturbed spectrum, possibly due to ^{39}Ar recoil, chlorite present, date is weighted average with a large assigned error to reflect low confidence in the analysis.
Crow Pass felsic intrusion (near Jewel mine)	50	54.1 ± 0.	$^{40}Ar/^{39}Ar$	white mica	This study	Plateau date, minor apparent argon loss, mica analyzed was Ca-rich from raw ^{39}Ar data, date is a cooling age.
Granite at Homestake mine	190		$^{40}Ar/^{39}Ar$	white mica	This study	Plateau date, minor apparent argon loss, mica analyzed was Ca-rich, good radiogenic yields, date is a cooling age.

*As used by Bradley et al. (1993).
†Dates were originally published in Borden et al. (1992) and Taylor et al. (1994), data are published for the first time in Data Repository item 9549

plutons or their aureoles, many veins cut turbidites far from large intrusions.

Gold-bearing quartz veins were emplaced in steeply dipping brittle faults and fractures after regional deformation and metamorphism of host rocks, and after intrusion of granitoids (Mitchell, 1979; Stuwe, 1986; Goldfarb et al., 1986). Large-scale brittle structures host economic ore concentrations, and small-scale brittle structures do not. The Chichagof district in southeast Alaska lies along the lengthy Border Ranges fault system and produced >24 900 kg (800 000 oz) gold. In the Chugach and Kenai mountains of south-central Alaska, none of the widespread veins in brittle faults and fractures produced more than 1550 kg (50 000 oz) gold.

Gold-vein mineralogy, isotopic signatures, and fluid-inclusion measurements are typical of mesothermal gold deposits and are consistent over a very wide area (Goldfarb et al., 1986). The compositions of the fluid inclusions in the gold-bearing quartz

bearing fluids may have been driven upward by thermal expansion of pore fluids and probably by tectonic forces. Fluid-pressure fluctuations resulted in hydraulic fracturing and episodic fluid flow above the brittle-ductile transition. These fractures developed into faults that may have accommodated strain caused by the high topography of the underthrust ridge. Gold-bearing quartz veins were then deposited as fluid pressures dropped. In addition, the rise of anatectic melts would have resulted in advective heat transport and associated hydrothermal fluid flow. This would lead to gold mineralization that consistently postdates emplacement of near-trench intrusions. The variation of isotopic ages between near-trench plutons and nearby gold occurrences suggests that hydrothermal systems were active for up to a few million years.

APPLICABILITY OF THE MODEL

Trench-ridge-trench triple junctions invariably produce slab windows. A trench-ridge-transform triple junction also generates a slab window and is essentially a special case of a trench-ridge-trench triple junction. The Mendocino trench-ridge-transform triple junction has migrated northward for the past ~29 m.y. (Atwater, 1989), leaving in its wake a region of high heat flow, volcanism, hot springs, and epithermal Hg-Au mineralization (Donnelly-Nolan et al., 1993). All of these effects can be attributed to heating the base of the continental lithosphere (Furlong et al., 1989). We suggest that similar shallow-level ore systems may have existed above the now-exposed veins in southern Alaska prior to uplift.

Except for Alaska and California, we are unaware of any other reported instances where gold mineralization can be directly attributed to a migrating slab window. A key for identifying such a tectonic setting would be the recognition of widespread, and probably diachronous, magmatism in ancient fore-arc settings. Slab windows form inevitably by plate motions at trench-ridge-trench and trench-ridge-transform triple junctions, and should have been even more common in the Archean, when there were perhaps five times as many plates and 10 times as many triple junctions as there are today (Abbott and Menke, 1990). Although many ancient lode-gold deposits have been broadly linked to collisional orogeny, some other deposits, Precambrian and Phanerozoic, may be more specifically linked to a slab window. For example, the Mother Lode region of California and the Westland gold district in New Zealand formed in fore-arc regions during enigmatic episodes of anomalous hydrothermal and magmatic activity.

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