Genetic links among fluid cycling, vein formation, regional deformation, and plutonism in the Juneau gold belt, southeastern Alaska

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ABSTRACT

Gold-bearing quartz vein systems in the Juneau gold belt formed within a 160-km-long by 5- to 8-km-wide zone along the western margin of the Coast Mountains, Alaska. Vein systems are spatially associated with shear zones adjacent to terrane-bounding, mid-Cretaceous thrust faults. Analysis of vein orientations and sense of shear data define a stress configuration with greatest and least principal axes oriented subhorizontally with northeast-southwest trends and subvertically, respectively. This local stress configuration is compatible with the far-field plate configuration during Eocene time. Isotopic ages of vein formation indicate that fluid cycling occurred between 56.5 and ≥52.8 Ma, and are consistent with a genetic link between veining and a change in plate motion in early Eocene time. Veining was also synchronous with the latter stages of rapid exhumation and voluminous plutonism immediately inboard of the gold belt. We propose a model in which interacting tectonic events facilitated fault-valve action and vein development along now-exhumed shear zones.

INTRODUCTION

Mesothermal gold-quartz veins provide some of the best fossil records of fluid cycling. Various workers have investigated the mechanisms of fluid cycling and vein development. Robert and Brown (1986) described the mechanical relation between shear and tensional veins on the ore-deposit scale. At the regional scale, Kerrich and Wyman (1990) proposed a link between mesothermal vein deposits and accretionary tectonics. To explain crustal hydraulics, Sibson (1981, 1990) and Sibson et al. (1988) developed the fault-valve model for fluid flow and cited compelling evidence for a genetic link between seismic activity and hydrothermal mineralization. Boullier and Robert (1992) substantiated the notion of significant fluid-pressure fluctuations associated with veining based upon microstructural and fluid-inclusion studies of gold-quartz vein systems.

Most studies of Mesozoic and older mesothermal vein deposits have indicated a long duration of hydrothermal activity. Geochronologic studies of vein deposits in Canadian Archean rocks have indicated that hydrothermal activity at several deposits in the Abitibi belt may have lasted over large time spans (up to 54 m.y.), on the basis of $^{40}Ar/^{39}Ar$ ages (Robert, 1990). Similarly, ages for Phanerozoic mesothermal vein deposits have suggested relatively long-lived hydrothermal episodes (tens of millions of years) in the Victoria region of Australia (Phillips, 1991), the Meguma terrane of eastern Canada (Kontak et al., 1990), and the Mother Lode of California (Bohlke and Kistler, 1986).

Eocene vein deposits in the Juneau gold belt provide an opportunity to investigate some of the youngest and best exposed mesothermal vein systems in the world. Located in northern southeastern Alaska, the Juneau gold belt is centered about a series of deeply exhumed fault zones that acted as fluid conduits for adjacent gold vein deposits. In contrast to data from pre-Cenozoic gold systems, a short-lived (~1 m.y.) crustal-scale dewatering event in the belt was described by Goldfarb et al. (1991) for the extensive vein formation. New isotopic ages, discussed below, indicate that this event occurred over about 3–3.5 m.y. More important is that the relations described herein provide insights into development of mesothermal vein systems and shed light on fluid-cycling processes within deep contractional fault zones. We propose a model in which fluid flow and gold deposition are temporally and genetically related to orogenic events in the fore arc of the Coast Mountains batholith.

GEOLOGY OF THE LODES

The Juneau gold belt consists of more than 200 gold-bearing quartz vein prospects and mines in a 5–8-km-wide zone striking northwestward for approximately 160 km between the Kensington deposit south to the Sumdum Chief mine (Fig. 1). Individual deposits range from isolated veins less than 1 m wide to vein systems up to 4 km long, 300 m wide, and at least 1–3 km deep. Gold-bearing veins were formed at 250–350 °C, and at depths of >4 km from fluids believed to have been derived from prograde metamorphic reactions (Goldfarb et al., 1988; Goldfarb, unpublished). Two deposits, the Alaska-Juneau and Treadwell, have been responsible for 90% of the 210 tonnes of gold produced from the belt since the 1880s.

Regional Setting

Veins in the Juneau gold belt are hosted by lithotectonic terranes that have been juxtaposed against one another along a system of west-verging, mid-Cretaceous thrust faults (Crawford et al., 1987; Gehrels et al., 1992; McClelland et al., 1992; Rubin et al., 1990; Gehrels, unpublished). Thrust faults strike northwestward and dip moderately to steeply eastward; older rocks to the east were systematically thrust westward over younger rocks. From the Coast Mountains batholith westward, mixed metasedimentary and metavolcanic rock sequences include (1) Carboniferous and older rocks of the Yukon-Tanana terrane (Gehrels et al., 1992); (2) Permian and Triassic rocks of the Taku terrane that are in contact with Yukon-Tanana terrane rocks along the Sumdum thrust fault (Gehrels et al., 1992); (3) Jurassic-Cretaceous rocks of the Gravina belt that are separated from rocks of the Taku terrane by the Fanshaw fault (Fig. 1).

Rocks throughout the belt were regionally metamorphosed to prehnite-pumpellyite facies by Cretaceous time. A Barrovian metamorphic event, beginning about 70 Ma, produced facies ranging from lower greenschist to upper amphibolite within the Yukon-Tanana and Taku terranes (Forbes, 1959; Himmelberg et al., 1991). Several major magmatic events also occurred between mid-Cretaceous and middle Eocene time. A suite of ~105 to 90 Ma diorite plutons was intruded into Gravina belt and Taku terrane rocks throughout the gold belt. Sheetlike to-

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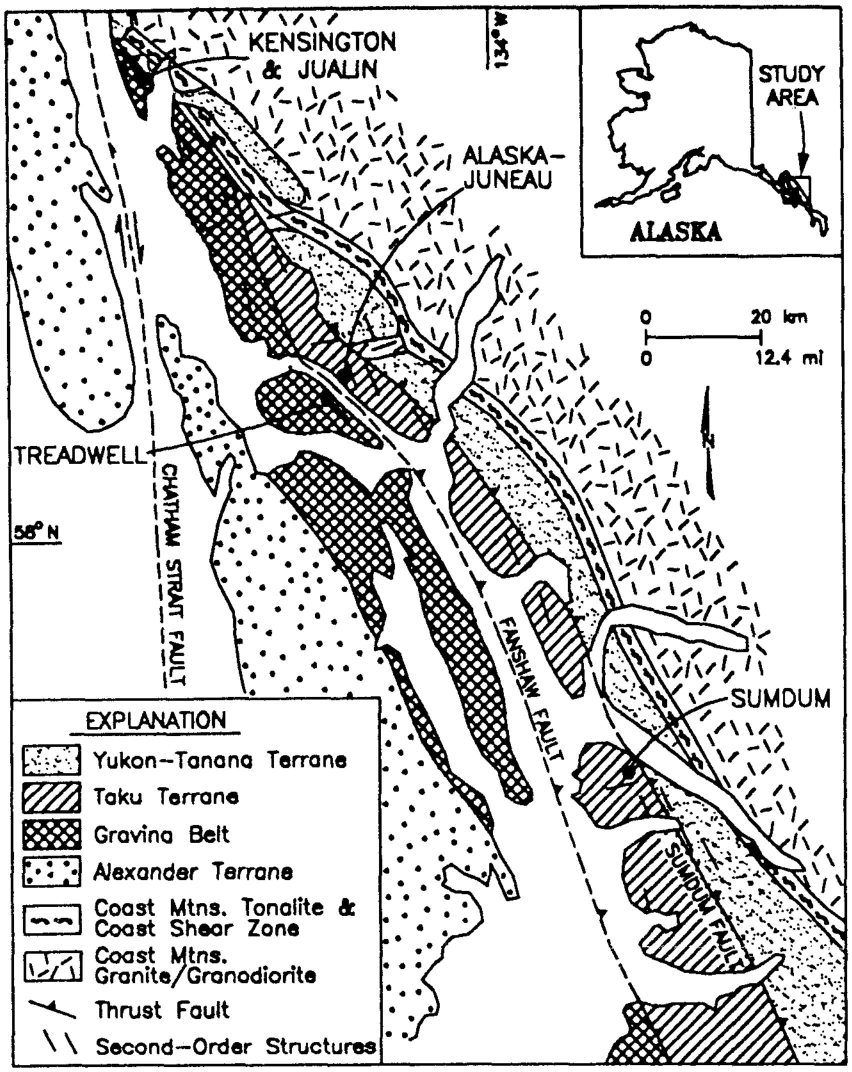

Figure 1. Location map of Juneau gold belt showing general geology, first- and second-order structures, and major vein deposits (labeled black areas).

nalite plutons were emplaced 5–10 km east of the gold belt between ~72 and ~58 Ma (Gehrels et al., 1991). The bulk of the intrusive suite in the region, located 15–20 km east of the gold belt, includes undeformed granite and granodiorite bodies that were emplaced between 55 and 48 Ma (Barker et al., 1986; Gehrels et al., 1991; Snee, unpublished data). Folding, thrust faulting, metamorphism, and plutonism in the region are products of a progressive compressional event that continued until late Paleocene–Eocene onset of dextral motion along the Denali–Chatham Strait fault system (Gehrels, unpublished; Miller and Gehrels, unpublished).

Structural Relations of the Auriferous Veins

The structural grain of the region is defined by a northwest-striking, moderately to steeply northeast-dipping, penetrative foliation that developed during progressive deformation between Cretaceous and Eocene time. The majority of the mineralized vein systems in the gold belt strike northwestward. First-order structural controls on the veins are the Fanshaw and Sumdum thrust faults (Fig. 1), which in many places coincide with a prominent topographic feature known as the Coast Range megalineament. Abundant quartz and carbonate veins within the fault zones suggest that these structures acted as fluid pathways. Second-order structures are defined at the deposit scale and are characterized by shear zones within 0.5 to 2 km of the Sumdum and Fanshaw faults. Third-order structures, sympathetic to second-order structures (Fig. 1), contain the gold-bearing veins. Third-order structures are composed of (1) *shear* veins, which strike northwest, dip steeply to the northeast, contain moderately north-northeast–plunging striations, and display evidence for right-lateral reverse displacement; (2) *hybrid* veins, which are east-northeast–striking, shear-tensional veins displaying shear steps indicative of left-lateral displacement and which are present within right-stepping, en echelon swarms, and (3) *tension* veins, which dip gently to the west and east (Table 1). Mutually crosscutting relations among the three vein types can be reconciled with a single regional stress regime in which the maximum principal stress was oriented subhorizontally in a northeast to southwest direction and the least principal stress was subvertical.

Age Relations of the Veins

Auriferous veins cut the regional metamorphic fabric and thus were emplaced after the Late Cretaceous to early Tertiary Barrovian dynamothermal event. $^{40}Ar/^{39}Ar$ ages of muscovites from veins from five of the major deposits in the belt confirm this observation and reveal that much of the vein emplacement occurred between 56 and 55 Ma (Goldfarb et al., 1991). Additional isotopic dates from the shear, hybrid, and tension veins indicate that veining was cyclic between about 56 and 53 Ma (Table 1). $^{40}Ar/^{39}Ar$ ages of 58–57 Ma from biotite collected from metamorphosed sedimentary rocks within the footwall of the Sumdum fault, as well as from ore-bearing diorite, indicate that rocks in the Taku terrane and Gravina belt were cooled below about 280 °C at least 1 m.y. prior to vein emplacement. Between the Alaska-Juneau and Treadwell deposits, biotite in greenstone within the Fanshaw fault zone yielded an $^{40}Ar/^{39}Ar$ age of 62 Ma. Finally, fluid inclusion studies and oxygen isotope geothermometry indicate that Kensington veins formed at ~350 °C, and the remainder of the deposits formed between ~250 and 300 °C. These temperatures are equivalent to the blocking temperature of muscovite and suggest that the veins were never subjected to temperatures higher than the blocking temperature of muscovite. Thus, the apparent ages of the veins are interpreted to reflect emplacement ages and not cooling ages.

TEMPORAL ASSOCIATION OF MINERALIZATION TO THERMAL EVENTS, EXHUMATION, AND FAR-FIELD PLATE-TECTONIC STRESSES

Magmatic activity in the Coast Mountains occurred prior to, during, and after auriferous vein emplacement. A major thermal event manifested by intrusion of the Coast Mountains batholith lasted from about 55 to 48 Ma (Barker et al., 1986; Gehrels et al., 1991; Snee, unpublished data) and is coeval with the ore-forming episode. The relation between this magmatic event and the gold-

TABLE 1. $^{40}Ar/^{39}Ar$ AGE SPECTRUM AND STRUCTURAL DATA FOR HYDROTHERMAL MUSCOVITES OF THIRD-ORDER VEINS

Deposit	Style*	Orientation (strike, dip*)	Apparent age (Ma)	1 σ	Percent ^{39}Ar on plateau
Kensington	Shear	335°, 65°	56.4	±0.2	24§#
	Shear	335°, 65°	54.2	±0.1	67
	Shear	330°, 60°	55.0	±0.1	87
	Shear	000°, 61°	55.3	±0.1	57
	Shear	350°, 65°	54.0	±0.1	94
	Hybrid	022°, 47°	54.4	±0.4	60
	Hybrid	075°, 85°	54.9	±0.2	73
	Tension	012°,32°; 180°,31°	53.5	±0.1	72
	Tension	000°, 25-35°	54.0	±0.1	62
	Tension	*	54.1	±0.1	60
	*	*	55.0†	±0.3	79
Jualin	Shear	335°, 61°	55.5†	±0.3	82
	Shear	335°, 65°	53.2	±0.1	66#
	Tension	020°, 25°	55.3	±0.3	78
Treadwell	Tension	*	52.8	±0.1	33§#
	Tension	*	55.1†	±0.2	10§#
Alaska-Juneau	Shear	330°, 60°	56.1†	±0.3	87
	Hybrid	070°, 75°	54.2	±0.1	76
Sumdum Chief	Hybrid	075°, 75°	55.1†	±0.2	95

Note: Apparent argon loss and apparent ages of an age spectrum step up from low- to high-extraction temperature.
*Indicates unknown style of orientation.
†Ages originally published in Goldfarb et al. (1991).
§Apparent age and percent ^{39}Ar reflect the maximum date of higher temperature steps in the age spectrum; therefore ages are minimum estimate.
#Apparent argon loss.

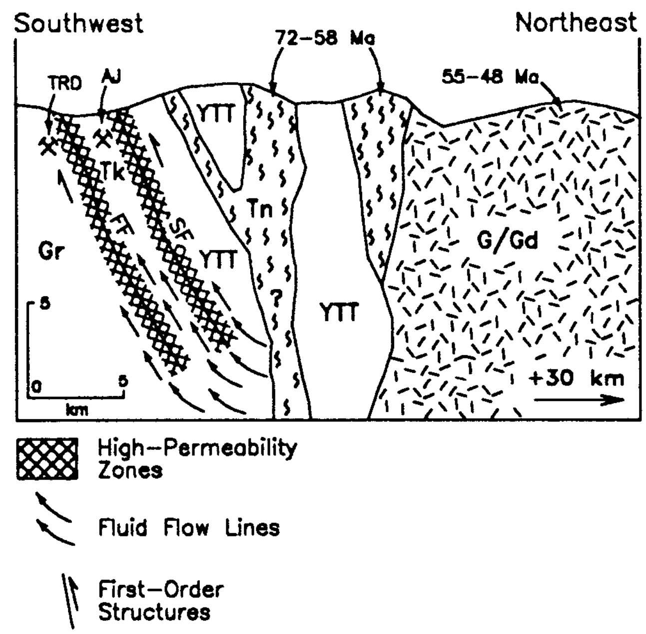

Figure 2. Schematic cross section looking to northwest through Treadwell (TRD) and Alaska-Juneau (AJ) deposits and showing first-order thrust faults, plutonic rocks, and inferred fluid-flow pathways. Arrow marked +30 km refers to distance batholith extends to east. Gr = Gravina belt, Tk = Taku terrane, YTT = Yukon-Tanana terrane, FF = Fanshaw fault, SF = Sumdum fault, Tn = tonalite sills, G/Gd = granites and granodiorites of Coast Mountains batholith.

bearing veins is not clear. The Eocene igneous rocks and veins are separated by 15–20 km at the present surface. Emplacement of a single large intrusion or multiple intrusions may have driven metamorphic fluids trapped in pore spaces up the east-dipping thrust faults. Rapid exhumation between 60 and 48 Ma (Hollister, 1982; Crawford et al., 1987) was contemporaneous with mineralization and plutonism along the western flank of the Coast Mountains. Changes in the orientation of the far-field stress configuration occurred during the early Eocene (Engebretson et al., 1985). A counterclockwise rotation in the direction of absolute motion of the Kula plate has been suggested to have occurred at about 56–55 Ma (Lonsdale, 1988), or 54–53 Ma (Cande and Kent, 1992). Vein geometries as noted above suggest that the near-field stresses during mineralization were compatible with far-field compression. Timing constraints on hydrothermal activity correlate well with changes in plate motion during which a transpressive regime may have been established. In such a case the vein deposits may have formed within compressional jogs along the transpressive zone.

INTEGRATED MODEL FOR VEIN DEVELOPMENT AND FLUID CYCLING

Our model for fluid flow and vein development is based on inferred genetic links between near-field processes of ductile-brittle faulting, exhumation, and heat flow, and on far-field plate motions. The synchroneity of plate-motion changes with the final stages of rapid uplift, the onset of dextral strike-slip, and a large thermal anomaly make it difficult to define any one process as responsible for vein development. But the fact that these thermotectonic events occurred simultaneously with vein development lends credibility to our model that fluid-cycling events and associated formation of gold-bearing veins are inherent fore-arc processes of orogenesis.

Migration of fluids into channelways could have been initiated by uplift, a thermal event, and/or a changing regional stress field. Rapid exhumation of overlying aquitards could aid vein development in two ways: volumetric expansion of water accompanying uplift can facilitate hydraulic fracturing (Norris and Henley, 1976), and unloading would decrease the vertical stress (least principal stress), thus enhancing the formation of shallowly dipping tensional veins. Magmatic heat could drive metamorphic pore fluids trapped in country rocks into permeable fault zones, and gold could be leached from country rocks during interconnection of flow channels and fluid advection (Fig. 2). Additionally, a shift from orthogonal to oblique convergence and the onset of transcurrent motion on northwest-striking structures would lower the effective mean stress and increase permeabilities.

Nowhere else do we know of a vein system of such magnitude in which individual mineralized structures can be shown to be mutually crosscutting and to have formed over 3–3.5 m.y. While this narrow age range may be one of the most tightly constrained among mesothermal vein systems, $^{40}Ar/^{39}Ar$ age data with a precision generally of ± 1–3×10^5 yr (1σ) provide only a maximum duration of the veining cycle. Yet this time span correlates with fluid cycling events which have been modeled to have periodicities of 10^3–10^5 yr (Nur and Walder, 1990), seismic events capable of rupture length/

width ratios of approximately 100 have periodicities of 10^2 yr (Sibson, 1990), and convective flow due to thermal pulses has periodicities of 10^3–10^5 yr (Norton, 1984; B. Dutrow and D. Norton, unpublished).

DISCUSSION

Crosscutting relations between and overlapping ages of different vein types illustrate the cyclic nature of the vein events reflective of variations in near-field stress axes due to fluid fluctuations (Boullier and Robert, 1992). Fault-valve behavior (Sibson, 1981, 1990; Sibson et al., 1988) due to contraction at a high angle to the first-order structures, best explains these observations and is compatible with the main mineralizing event being associated with local compressional jogs in a transpressive zone due to overall far-field compression. The ultimate control on the fluid flow and emplacement of the veins was tied to a feedback loop between near-field processes and far-field stress configurations between ~56 and 52 Ma. Near-field processes include plutonism that could have affected the thermal regime and fluid flow in the vicinity of the gold deposits (Fig. 2). Exhumation may have facilitated veining due to the volumetric expansion of water, and/or it may have lowered the vertical stress as unroofing progressed. Last, a change in the local stress regime, due to a switch in far-field plate motions from normal convergence to oblique convergence, may have decreased the normal stress across the region, resulting in increased permeabilities along or near major fault zones (Fig. 2).

The synchroneity of fluid flow and fracture development with the final stages of regional exhumation, a large thermal event, and changes in plate motion may be an essential combination of processes necessary for gold-vein mineralization. It is only within such young systems as the Juneau gold belt that recognition of these tectonic processes and the ability to correlate ore-controlling mesoscopic structures with far-field stresses is readily feasible.

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REFERENCES CITED

Barker, F., Arth, J.G., and Stern, T.W., 1986, Evolution of the Coast Batholith along the Skagway traverse, Alaska and British Columbia: American Mineralogist, v. 71, p. 632–643.

Barton, M.D., and Hanson, R.B., 1989, Magmatism and the development of low-pressure metamorphic belts: Implications from the western United States and thermal modeling: Geological Society of America Bulletin, v. 101, p. 1051–1065.

Bohlke, J.K., and Kistler, R.W., 1986, Rb-Sr, K-Ar, and stable isotope evidence for the 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.

Boullier, A-M., and Robert, F., 1992, Palaeoseismic events recorded in Archean gold-quartz vein networks, Val d'Or, Abitibi, Quebec, Canada: Journal of Structural Geology, v. 14, p. 161–179.

Cande, S.C., and Kent, D.V., 1992, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 97, p. 13,917–13,951.

Crawford, M.L., Hollister, L.S., and Woodsworth, G.J., 1987, Crustal deformation and regional metamorphism across a terrane boundary, Coast plutonic complex, British Columbia: Tectonics, v. 6, p. 343–361.

Engebretson, D.C., Cox, A., and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific basin: Geological Society of America Special Paper 206, 64 p.

Forbes, R.B., 1959, The geology and petrology of the Juneau Icefield area, southeastern Alaska [Ph.D. thesis]: Seattle, University of Washington, 261 p.

Gehrels, G.E., McClelland, W.C., Samson, S.D., Patchett, P.J., and Brew, D.A., 1991, U-Pb geochronology of Late Cretaceous and early Tertiary plutons of the northern Coast Mountains batholith: Canadian Journal of Earth Sciences, v. 28, p. 899–911.

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

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

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

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

Hollister, L.S., 1982, Metamorphic evidence for rapid (2 mm/yr.) uplift of a portion of the Central Gneiss Complex, Coast Mountains, British Columbia: Canadian Mineralogist, v. 20, p. 319–332.

Kerrich, R., and Wyman, D., 1990, Geodynamic setting of mesothermal gold deposits: An association with accretionary regimes: Geology, v. 18, p. 882–885.

Kontak, D.J., Smith, P.K., Reynolds, P., and Taylor, K., 1990, Geological and $^{40}Ar/^{39}Ar$ geochronological constraints on the timing of quartz vein formation in Meguma group lode-gold deposits, Nova Scotia: Atlantic Geology, v. 26, p. 201–227.

Lonsdale, P., 1988, Paleogene history of the Kula plate: Offshore evidence and onshore implications: Geological Society of America Bulletin, v. 100, p. 733–754.

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

Norris, R.J., and Henley, R.W., 1976, Dewatering of a metamorphic pile: Geology, v. 4, p. 33–36.

Norton, D., 1984, A theory of hydrothermal systems: Annual Reviews of Earth and Planetary Sciences, v. 12, p. 155–177.

Nur, A., and Walder, J., 1990, Time-dependent hydraulics of the earth's crust, *in* Geophysics Study Commission on Geosciences, Environment, and Resources: The role of fluids in crustal processes: Washington, D.C., National Academy Press, p. 113–127.

Phillips, G.N., 1991, Gold deposits of Victoria: A major province within a Palaeozoic sedimentary succession, *in* World Gold '91: Melbourne, Australian Institute of Mining and Metallurgy, p. 237–245.

Robert, F., 1990, Dating old gold deposits: Nature, v. 346, p. 792–793.

Robert, F., and Brown, A.C., 1986, Archean gold bearing quartz veins at the Sigma mine, Abitibi greenstone belt, Quebec: Part I. Geologic relations and formation of the vein system: Economic Geology, v. 81, p. 578–592.

Rubin, C.M., Saleeby, J.B., Cowan, D.S., Brandon, M.T., and McGroder, M.F., 1990, Regionally extensive mid-Cretaceous west-vergent thrust system in the northwestern Cordillera: Implications for continental margin tectonism: Geology, v. 18, p. 276–280.

Sibson, R.H., 1981, Fluid flow accompanying faulting: Field evidence and models, *in* Simpson, D., and Richards, P., eds., Earthquake prediction, an international review: American Geophysical Union Maurice Ewing Series, v. 6, p. 593–603.

Sibson, R.H., 1990, Faulting and fluid flow: Mineralogical Association of Canada Short Course, v. 18, p. 93–132.

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

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