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Fluid mixing in orogenic gold deposits: Evidence from the H-O-Sr isotope composition of the Val-d'Or vein field (Abitibi, Canada)

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ABSTRACT

Quartz and tourmaline from the Val-d'Or, Québec (Canada) orogenic gold vein field have oxygen isotope fractionation indicating equilibrium over a range of temperature (280–492 °C). The range of $\delta^{18}O$ values is from 9.2 to13.8‰, and from 6.5 to 9.5‰, for quartz and tourmaline, respectively. The hydrogen isotope composition of tourmaline has a range from −63 to −13‰. The initial Sr isotope composition ($^{87}Sr/^{86}Sr_{(i)}$) of vein tourmaline at the time of mineralization ranged from 0.700710 to 0.702246. Vein carbonates have a similar range in Sr isotope composition, form 0.701243 to 0.703641. A series of samples from the Sigma deposit displays no systematic variation with depth for $\delta^{18}O$ values of quartz or tourmaline, δD values of tourmaline, temperature of equilibrium, or $^{87}Sr/^{86}Sr_{(i)}$. The $^{87}Sr/^{86}Sr_{(i)}$ of local komatiite, basalt, andesite, grauwacke and granodiorite, at 2.7 Ga, ranged from 0.681971 to 0.7128706. Country rocks with low $^{87}Sr/^{86}Sr_{(i)}$ are likely a consequence of hydrothermal resetting of the Rb/Sr system in these samples.

Covariation of the calculated equilibrium δD_{H2O} and $\delta^{18}O_{H2O}$ with quartz-tourmaline equilibrium temperatures indicates mixing between a low-$\delta^{18}O$ (<1.5‰), high δD (>−10‰), low temperature (<280 °C) upper crustal fluid, and a high-$\delta^{18}O$ (>9.3‰), low δD (<−40‰), high temperature (>490 °C) deep-seated metamorphic fluid. At temperatures below the critical point for low-salinity hydrothermal fluids, δD_{H2O} are affected by liquid-vapour phase separation, yielding the high δD values characteristic of the upper crustal fluid. A broad covariation between $\delta^{18}O_{H2O}$ and the $^{87}Sr/^{86}Sr_{(i)}$ of tourmaline is consistent with mixing of two fluids from two reservoirs with different Sr concentrations and $\delta^{18}O_{H2O}$ values. The low $^{87}Sr/^{86}Sr_{(i)}$ (<0.7007) inferred for the deep-seated metamorphic fluid end-member is consistent with Archean prograde metamorphic dewatering of typical volcanic and sedimentary country rocks of the Val-d'Or area. The higher $^{87}Sr/^{86}Sr_{(i)}$ (>0.7022) of the upper crustal fluid end-member most likely resulted from a long history of water-rock exchange between Archean seawater and carbonate and radiogenic plutonic rocks of the Abitibi sub-province.

1. Introduction

Orogenic gold deposits consist of auriferous quartz veins with carbonate, sulphide, and a range of accessory minerals including tourmaline (Goldfarb et al., 2005). The quartz in many deposits forms ribboned lenses in steeply dipping reverse shear zones, or flat to shallow-dipping extensional veins. The auriferous quartz vein fields are interpreted to have formed near the base of the seismogenic crust and in the vicinity of major crustal faults (Boullier and Robert, 1992; Groves et al., 1998; Sibson et al., 1988). These fractured domains of the seismogenic crust are interpreted to represent openings during fluid pressure build-up before, and during aftershock slip following major earthquakes (Boullier and Robert, 1992). These gold deposits are hosted in metamorphic belts that formed in transpressional orogens (Goldfarb et al., 2005; Groves et al., 1998; Groves et al., 2003; Kerrich and Wyman, 1990). This geological setting allows studying the infiltration of deep-seated hydrothermal fluids and their interaction with the country rocks in a fossilized hydrothermal system.

The Val-d'Or orogenic gold vein field, Abitibi, Canada (Robert, 1994), is a classical example of this type of deposit with a well-constrained geological setting. The Val-d'Or vein field contains a large number of quartz-tourmaline-carbonate veins with a homogeneous mineralogy, formed in the same structural setting, and interpreted to have formed in a single hydrothermal system (Robert, 1994). The stable isotope compositions (C, O, S) of orogenic gold quartz veins of the Val-d'Or vein field have been documented in detail at the deposit and vein field scales (Beaudoin and Pitre, 2005), who showed that the stable isotope systematics were the result of fluid-rock reaction and mixing between an upper crustal fluid and a deep-seated metamorphic hydrothermal fluid. The regional pattern of vein quartz oxygen isotope composition was reproduced using 3D numerical models simulating transport, reaction and mixing, to demonstrate that the major crustal shear zone controlling the distribution and structural evolution of the auriferous

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orogenic veins functioned as an episodic hydraulic drain during seismic events (Beaudoin et al., 2006).

This paper presents oxygen isotope composition from coexisting quartz and tourmaline, hydrogen isotope composition from tourmaline, and Rb, Sr and $^{87}Sr/^{86}Sr$ data from vein tourmaline and carbonate, as well as representative volcanic, plutonic and sedimentary country rocks. It provides, to date, the most detailed documentation of the combined H-O-Sr isotope systems in vein minerals at the scale of an orogenic gold vein field. The combination of stable and radiogenic isotope systems is used to assess isotope equilibrium as well as hydrothermal fluid compositions and sources that formed the gold veins of the Val-d'Or vein field. The auriferous fluid compositions and sources in the Val-d'Or vein field are compared to those for other orogenic gold districts to show that fluid mixing is a more common process than commonly recognized in orogenic gold deposits.

2. Geological setting

The Val-d'Or orogenic gold vein field is located at the boundary between the Abitibi volcanic and the Pontiac sedimentary sub-provinces of the Archean Superior Province in Canada (Card and Ciesielski, 1986). The Cadillac-Larder Lake Tectonic Zone (CLLTZ), a major reverse shear zone >200 km long and with a steep dip to the north (Robert et al., 1995), separates the Abitibi and Pontiac sub-provinces (Fig. 1). The volcanic rocks of the Abitibi sub-province host most of the quartz-tourmaline-carbonate veins, although some veins also occur within the metasedimentary rocks of the Pontiac sub-province immediately south of the CLLTZ (Fig. 1). The volcanic rocks consist of tholeiitic ultramafic to calc-alkaline felsic rocks that erupted between 2714 Ma and 2702 Ma (Pilote et al., 1998; Scott et al., 2002). Desrochers and Hubert (1996) proposed that ultramafic and mafic rocks formed several terranes that were accreted to form the Malartic Composite Block during a first phase of deformation (D_1). They interpreted the calc-alkaline felsic volcanic and volcanoclastic rocks of the Val-d'Or Formation to be deposited above an angular discordance. Scott et al. (2002), however consider that the Val-d'Or Formation is in gradational contact with the underlying mafic rocks. The volcanic pile was intruded by the synvolcanic Bourlamaque Batholith at 2700 Ma (Wong et al. 1991). A second phase of deformation (D_2) was responsible for the dominant E-W foliation that formed during an oblique collision event (Robert 1989; Desrochers and Hubert 1996) that ended with a dextral transcurrent deformation event (D_3) along the CLLTZ (Robert et al., 1995; Neumayr et al., 2000). D_2 shortening was accommodated by a series of dominantly E-W subvertical to moderately-dipping reverse shear zones that contain the orogenic gold quartz-tourmaline carbonate veins. Prograde greenschist metamorphism associated with D_2 peaked before 2693 Ma (Hanes et al. 1992) to 2677 Ma (Feng et al., 1992). Syn- to late-tectonic plutons have ages ranging from 2694 Ma to 2680 Ma (Wong et al., 1991; Jemielita et al., 1990; Zheng, 1993; Couture et al., 1994; Morasse et al., 1995).

2.1. Orogenic gold quartz veins

Cross-cutting relationships between shear zone-hosted gold quartz veins and 2690–2685 Ma syntectonic intrusions indicate two events of gold mineralization (Robert, 1994; Couture et al., 1994; Pilote et al., 1998). Early quartz-carbonate auriferous veins are commonly folded and boudinaged within sub-vertical shear zones and cut by dykes (Couture et al., 1994; Robert, 1994). The more abundant, younger auriferous quartz-tourmaline-carbonate veins crosscut all intrusive rocks of the region (Robert et al., 1995). The veins form either fault-filled quartz lenses in sub-vertical reverse shear zones, or sub-horizontal extensional veins near the shear zones (Robert et al., 1995).

The samples come from both sub-vertical and from sub-horizontal veins where quartz and tourmaline are intergrown. The proportion of quartz and tourmaline in the vein samples varies from <5% to >50% tourmaline. Beaudoin and Pitre (2005) showed that there is no systematic variation in oxygen isotope composition from various textural types of quartz in vein, between sub-horizontal extensional and sub-vertical shear veins, and along strike or down-dip within a vein system. A systematic change in $\delta^{18}O$ values, however, was shown for different deposits. The samples selected for this study are representative of the range in $\delta^{18}O$ values and spatial distribution within the Val-d'Or vein field (Beaudoin and Pitre, 2005; Olivo et al., 2006).

3. Analytical methods

Quartz, tourmaline and carbonate concentrates were handpicked under a binocular microscope. Sub-samples of quartz and tourmaline, weighing 7–10 mg, were reacted with BrF_5 according to the method of Clayton and Mayeda (1963) at the Stable Isotope Laboratory of Université Laval. The evolved CO_2 was analyzed by IRMS at the G.G. Hatch Laboratory of the University of Ottawa. Oxygen isotope ratios are reported in the δ-notation relative to V-SMOW with a precision better than 0.2‰ (1σ). Accuracy and precision of $\delta^{18}O$ values was verified by analysis of NBS-28. Tourmaline hydrogen isotope composition was measured using a Carlo Erba Elemental Analyzer NCS2500 coupled to a Finnigan MAT 252 Isotope Ratio Mass Spectrometer at Queen's Isotope

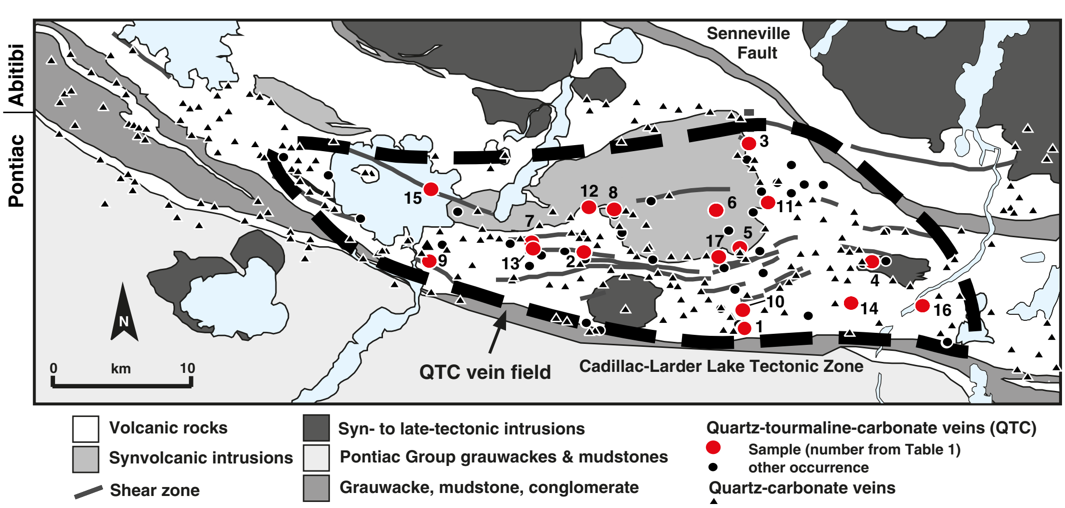

Fig. 1. Regional geology map of the Val-d'Or orogenic gold vein field showing the location of the quartz-tourmaline-carbonate and quartz-carbonate veins studied (modified from Beaudoin and Pitre, 2005).