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MORITZ, Robert, CROCKET, James H.


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Mechanics of formation of the gold-bearing quartz–fuchsite vein at the Dome mine, Timmins area, Ontario

ROBERT P. MORITZ and JAMES H. CROCKET

Department of Geology, McMaster University, 1280 Main Street West, Hamilton, Ont., Canada L8S 4M1

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The highest grade orebody in the Dome mine is a steeply dipping 500 m long, 550 m high, and 3.5 m wide banded quartz–fuchsite vein (QFV) accompanied by subsidiary veins in the adjacent wall rock. The QFV is located in a subvertical zone of carbonatized komatiite near a slate unit and is composed of relatively unstrained massive quartz and strained ribbon quartz. Fuchsite and chlorite are the main ribbon components. Native gold, galena and tellurides are typically associated with ribbon quartz, whereas massive quartz is usually low grade.

The quartz–fuchsite vein system is coeval with the regional penetrative deformation. Reverse oblique-slip faulting together with an intricate interplay between intermittent variations of the deviatoric stress regime and strain refraction due to layer anisotropy explain the overall anatomy of the vein system. The regional compressive stress regime and the syntectonic wall-rock alteration created the favorable requirements for the combined shear and hydraulic fracturing that led to vein formation.

Massive quartz was deposited during prolonged episodes of vein growth, whereas ribbon quartz was emplaced in the course of repetitive and brief periods of crack-seal vein growth. The systematic association of high-grade ore with ribbon quartz suggests a genetic link whereby gold deposition is attributed to small pressure drops accompanying the crack-seal mechanism of vein growth. Thus, gold was introduced along with the bulk of the quartz.

Le minerai de plus haute teneur de la mine Dome est une veine rubanée subverticale à quartz–fuchsite de 500 m de long, ayant une extension verticale de 550 m et 3.5 m de puissance, accompagnée de veines de quartz subsidières. La veine de quartz–fuchsite est encaissée dans une zone subverticale de komatiite carbonatée proche du contact avec une unité de schiste ardoisié. Les veines sont composées de quartz massif peu déformé et de quartz à texture rubanée, laminée, ce dernier étant plus fortement déformé. Les laminae sont essentiellement constituées de fuchsite et de chlorite. L’or natif, la galène et les tellurures sont associés au quartz rubané, alors que le quartz massif est le plus généralement stérile.

La mise en place de la veine de quartz–fuchsite et des veines subsidiaires est contemporaine à la déformation pénétrative régionale. Le rejet inverse et oblique le long d’une faille subverticale lors d’un cisaillement simple explique en grande partie la disposition spatiale des veines, qui est toutefois compliquée en raison de variations de l’intensité des contraintes tectoniques et de l’orientation des axes de contraintes au travers de lithologies de compétences diverses. La compression régionale et l’altération syntaxtonique des roches encaissantes ont créé les conditions propices à la formation des veines dans des fractures induites par cisaillement et par fracturation hydraulique.

Le quartz massif a été précipité lors de périodes prolongées de remplissage de fractures en ouverture simple, alors que le quartz rubané a été formé lors de brèves épisodes répétitifs de «crack-seal». L’association systématique des fortes valeurs aurifères avec le quartz rubané suggère un lien génetique. La précipitation de l’or est attribuée aux légères baisses de pression associées au mécanisme de «crack-seal». L’or a donc été introduit en même temps que la majeure partie du quartz.


Introduction

The timing of regional penetrative deformation and gold mineralization is still a matter of some controversy in the Timmins mining camp of Ontario, due in large part to the great diversity of the structural and lithological setting of the orebodies. As a contribution to the question of timing, this paper presents the results of a structural study that was part of an integrated field, petrographic, geochemical and fluid-inclusion investigation of the high-grade quartz–fuchsite vein at the Dome mine (Moritz 1988; Moritz and Crocket 1989; Moritz et al. 1990). The approach taken in this study was (i) to define the structural setting of the vein system and place the latter in the geological evolution of the Timmins area, (ii) to determine the mechanism of veining, (iii) to work out the gold distribution in the vein, and finally, (iv) to understand how gold deposition is related to vein development and regional deformation.

The Timmins area is located near the southwestern border of the Abitibi greenstone belt along the major east–west-striking Destor–Porcupine break (Goodwin and Ridler 1970; Hodgson 1986). The geology of the Timmins mining camp has been discussed by Ferguson et al. (1968), Roberts (1981), Pyke (1982), Hodgson (1983, 1986), and Mason et al. (1988) and is synthesized in Fig. 1. The major lithologies are komatiitic to tholeiitic to calc-alkaline volcanic rocks. Metasedimentary rocks consist dominantly of interlayered wacke, siltstone, and conglomerate. Quartz–feldspar porphyries and late albite dikes intrude the volcano-sedimentary lithologies. The porphyries yield U–Pb zircon ages ranging between 2688 ± 2 and 2691 ± 3 Ma, and one albite dike has been dated at 2673 ± 5 Ma (Marmont and Corfu 1989). All rocks, except late diabase dikes, have been metamorphosed to the lower green schist facies (Jolly 1978) and have been affected by a penetrative east-trending foliation and east-plunging lineation (Roberts et al. 1978; Roberts 1981; Hodgson 1983, 1986; Mason et al. 1988).

The gold deposits are in close proximity to and postdate the porphyries and the albite dikes (Hodgson 1983, 1986; Mason and Melnik 1986; Wood et al. 1986; Mason et al. 1988) (Fig. 1). An intense carbonate alteration usually accompanies gold mineralization (Ferguson et al. 1968; Pyke 1982; Hodgson 1983; Fyoon 1986; Mason et al. 1988) and is thought either to predate or to be coeval with regional deformation and green schist metamorphism (Fyoon 1986). Fuchsite associated with gold mineralization yields a minimum 40Ar/39Ar formation age, and by inference a time of gold deposition of 2633 ± 6 and 2617
± 8 Ma at the Dome mine and the Hollinger mine, respectively (Masliwec et al. 1986).

**Dome mine geology**

The Dome mine lies on the south limb of the Porcupine syncline, about 1 km north of the Destor–Porcupine fault (Fig. 1). In the central part of the mine, a folded assemblage of mafic volcanic flows overlie slate and conglomerate plunges northeast. The southwestern part of the mine is occupied by two major quartz–feldspar porphyries, the Preston and Paymaster (Holmes 1968; Rogers 1982) (Fig. 2). All the porphyries of the mine have been intensely albitized, sericitized, and carbonatized with obliteration of primary textures, so little is known about their original nature (McAuley 1983). The southeastern part of the mine is dominated by a series of south-dipping massive mafic flows.

A northeast-trending and southeast-dipping zone of carbonatized rocks and altered porphyry lenses separates the south-dipping mafic rocks from the metasedimentary rocks (Holmes 1968; Rogers 1982). The protolith of the carbonatized rock is interpreted to be a volcanic series of komatiitic composition (Fryer et al. 1979; Roberts and Reading 1981; Moritz 1988). The zone of carbonatized rocks and altered porphyries is considered to be the trace of the Dome fault, a branch of the major Destor–Porcupine break (Holmes 1968; Davies 1977; Hodgson 1983; Piroshco and Kettles 1988; Roberts and Stevens 1989).

**Description of the quartz–fuchsite vein system**

*Geological setting*

The quartz–fuchsite vein system is in the northeastern part of the Dome mine, in the zone of carbonatized komatiite and altered porphyries (Fig. 2), and occurs between the 6th and 17th levels of the mine. Two groups of quartz veins can be distinguished. The main mass of quartz is a 500 m long composite vein with a 550 m vertical extension and an average thickness of 3.5 m which is referred to as the quartz–fuchsite vein (QVF). A second type of quartz veining, subsidiary in mass to the QVF, occurs in the wall rock adjacent to the QVF and is largely discordant with respect to the QVF.

The QVF is discontinuous along strike and dip. The vein strikes northeast and commonly dips steeply towards the southeast (Figs. 3, 4A). It is subparallel to the northern contact of the altered komatiite with a unit of slate (Figs. 2, 3). The immediate wall rock is mainly carbonatized komatiite, although the QVF sometimes marks the contact between the ultramafic rock and the slate. No distinctive and spatially related hydrothermal alteration could be recognized about most of the vertical extension of the quartz–fuchsite vein system (Moritz 1988). It suggests that the hydrothermal fluid which formed the vein system was essentially at thermal and compositional equilibrium with local wall rocks, in particular the altered komatiite. The carbonatized wall rock is composed of magnesite, ferroan dolomite, quartz, and chlorite. Despite the high fuchsite content of the QVF, the immediate wall rock usually contains little to no fuchsite. However, on the 8th level and above, a fuchsite–pyrite alteration halo is developed around the QVF in its western section.

In the vicinity of the QVF, the regional foliation, as defined by Roberts et al. (1978) and Roberts (1981), is indicated by preferential alignment of chlorite, mica, and carbonates. It strikes northeast, dipping steeply northwest (Fig. 4A). In many places, the regional foliation is discordant with respect to the QVF (Figs. 5A, 5B). Locally, an additional cleavage is
developed in the wall rock. The latter planar fabric strikes northwest and dips northeast (Fig. 4A). No stretch lineation could be recognized in the wall rock in the neighborhood of the QFV.

Quartz–fuchsite vein

The QFV is composed of massive and ribbon quartz (Fig. 5C). The former consists almost entirely of relatively unstrained large quartz grains, whereas the latter is characterized by alternating bands of quartz, and phyllosilicates and (or) wall rock. Such banded quartz is variably termed laminated, layered, ribbon, and book textured quartz in the literature (e.g., Chace 1949; McKinstry and Ohle 1949; Mawer 1987; Hodgson 1989). In the following, banded and ribbon quartz are used as synonymous terms. The temporal relationship between the two types of quartz material is ambiguous, because massive quartz crosscuts the ribbon quartz and in turn is locally truncated by ribbon quartz. It suggests that the two quartz types are broadly contemporaneous.

The mode of occurrence of the massive, relatively unstrained quartz is variable. The QFV may be composed entirely of such massive quartz. Often, lenses of massive quartz separate zones of ribbon-textured quartz (Fig. 5C). In other settings, individual massive quartz domains are outlined by wall-rock inclusions. In a few localities, the massive quartz has a smoky appearance, and centimetre-sized smoky quartz elements may be surrounded by white quartz in a patchwork-like pattern.

Banding is roughly subparallel to the walls of the QFV (Figs. 5B–5D). Banding consists of several subparallel individual quartz-dominated and phyllosilicate-dominated ribbons. The width of individual phyllosilicate-dominated ribbons is in the millimetre range, whereas quartz ribbons may attain thicknesses in the centimetre range. Thicker phyllosilicate-dominated bands can be recognized as slivers or inclusions of slate or foliated carbonatized komatite. In detail, the ribbons are highly irregular and discontinuous. The banding can be parallel to one wall of the vein, bend towards the opposite wall, and become transgressive with respect to the general trend of the vein. One set of parallel bands may be truncated by another. The ribbon quartz also exhibits deformation with boudinage (Figs. 5C–5D), folding (Fig. 5E), and stylolitization (Fig. 5F).

Quartz within the banded domains displays undulose extinction and pressure-dissolution features, and is often largely recrystallized and subgrained (Fig. 5F). Quartz is usually not continuous in shape or optical orientation across a single phyllosilicate ribbon. In some rare cases, however, phyllosili-
Fig. 3. Vertical section through the zone of carbonatized rocks and altered porphyries in the western part of the quartz-fuchsite vein (see Fig. 2 for location of the cross section).

cate laminae and inclusion trails have been observed in crystallographically continuous quartz grains from the banded domains (Fig. 5F). In such occurrences, the laminae and the trails do not cross the grain boundaries but appear to die out where the grain is recrystallized. This microstructure is typical of veining caused by crack-seal (Ramsay 1980a; Cox and Etheridge 1983).

The phyllosilicate-dominated ribbons contain fuchsite and (or) chlorite as essential minerals and may grade into inclusions of carbonatized komatite or slate. Other mineral components of the ribbons are carbonates, rutile, pyrite, and occasionally tourmaline. Late-stage carbonates are present along fractures in quartz-dominated ribbons and may replace quartz. The principal opaque minerals are native gold, galena, altaite and melonite, with accessory hessite and tellurobismuthite. These minerals are commonly intergrown, and galena and melonite contain inclusions of altaite, tellurobismuthite, and hessite. Native gold and galena are consistently associated in the QFV and, along with the other opaque minerals, are commonly present only in ribbon quartz. They occur within fractures in quartz, between quartz grains, and along the phyllosilicate-dominated bands. In rare cases where gold and galena occur in massive quartz, they are located at the contact with carbonatized wall rock. The strain shown by the ribbon quartz and the lack of diagnostic intermineral textures preclude the determination of a depositional paragenesis, and it is assumed that the opaque minerals are coeval. Such contemporaneity of gold, tellurides, and galena has been described for other gold deposits in the Timmins area (Hurst 1935; Keys 1940; Ferguson et al. 1968). Pyrite is rare in the QFV and adjacent wall rocks. Where it does occur, pyrite is usually located along the phyllosilicate-dominated bands, or within quartz in the banded domains of the QFV. It does not show any specific relationship with respect to gold or other mineral phases.

Discordant quartz veins crosscut the ribbon quartz at high angle (Fig. 5C). These veins range in width and length from a few millimetres to several centimetres locally up to 2 or 3 m. Some of the smaller crosscutting veins seem to be related to the boudinage of the banded quartz (Fig. 5C). The quartz in these small “ladder” veins is less strained than the quartz within the banded domains of the QFV. In some occurrences, where boudinage affects the entire QFV, a small sigmoidal vein occupies the pinch of the boudinage structure (Fig. 5D).

Contractional faults with both left- and right-handed motions are present in the QFV. The QFV is locally folded (Fig. 6A), but orientations of fold axes could not be measured with confidence. Slickenside striations are common along both the phyllosilicate ribbons and the walls of the QFV. They plunge to the east (Fig. 4B), parallel to all linear structures in the Dome mine (Holmes 1968) and to the regional stretching lineation (Roberts et al. 1978; Roberts 1981).

The QFV can be subdivided into three zones based on the abundance of ribbon-textured quartz. Ribbon quartz is predominant in the western and eastern parts of the vein, whereas the central portion of the vein is mainly composed of massive quartz (Fig. 2B). The banding in the western part is due chiefly to fuchsite, whereas chloride ribbons predominate in the eastern part.

Quartz veining in the wall rock

Veining in the wall rock of the QFV is confined mainly to the carbonatized komatite, although some veining extends into adjacent slate. The relative ages of the wall-rock veins and the QFV are equivocal, since each one can be found to crosscut the other. Some of the veins in the wall rock pass gradually into the QFV. It suggests contemporaneity between the QFV and the veins in the wall rock. Quartz veins of various configurations occur. Straight, parallel-walled veins of relatively uniform width are the most common. An overall coherent distribution pattern cannot be recognized for relatively undeformed veins in the wall rock (Fig. 4C). However, some specific relationships emerge by detailed studies of individual sites. Some sets of subhorizontal veins which are perpendicular to the QFV are opened normal to the slickenside striation observed along the QFV (Fig. 6B). Other veins are subvertical and oriented normal to both the QFV and the subhorizontal veins (Figs. 6C, 6D). Systems of horizontal quartz veins connected by vertical quartz veins suggest contemporaneity of the subhorizontal and subvertical vein sets (Fig. 6E). Locally, small sigmoidal en echelon veins occur (Fig. 6F). Such veining is subsidiary in mass to the QFV and to the subvertical and subhorizontal veins. The en echelon vein arrays indicate both left-hand and right-hand displacements. Breccias occur as well. They consist of angular to subangular, centimetre- to metre-sized carbonatized wall-rock fragments, which are embedded in a matrix of quartz.

The quartz veins in the wall rock display a state of deformation ranging from unstrained to tightly and isoclinally
folded (Fig. 5A). Besides isoclinal folding, deformation also includes boudinage, fracturing, and (or) deflection of wall-rock veins into parallelism with the QFV (Fig. 6B). Most of the veins in the wall rock are unbounded and composed of quartz alone, suggesting they were formed during a single opening stage. Banded veins have been recognized in some instances, and indicate occasional incremental opening. Some of the veins show the development of quartz crystals perpendicular to the walls of the veins, whereas others show slickensides along the walls. This indicates veining took place in both pure extension and shear-induced fractures. Very few wall-rock veins contain visible gold and galena.

**Distribution of gold in the quartz–fuchsite vein**

The QFV is the highest grade ore in the Dome mine (Rogers 1982). Economic gold concentrations are typically present only in fuchsite- and (or) chlorite-banded domains. Ribbon quartz and galena are key indicators of high-grade gold zones. “Ladder” veins crosscutting the banding do not contain visible gold, and massive, unbounded quartz is usually barren or low grade. At shallow stoping levels (e.g., stope 1081 #1 just below the 8th level), where the fuchsite–pyrite halo surrounds the QFV, economic gold concentrations occur in the wall rock adjacent to the vein, and some visible gold is in massive quartz attached to the wall rock. According to D. S. Rogers (personal communication, 1985), this is common on the 6th and 8th levels.

Two high-grade-ore zones can be recognized in the QFV. They correspond to the two areas with abundant fuchsite–chlorite ribbons (Fig. 2B). The highest grades are in the western portion of the QFV, and a second high-grade zone is located in the upper part of the eastern extension. Both high-grade zones are ellipsoidal in shape in longitudinal section (Fig. 7), with long axes plunging to the northeast similarly to the trend of the slickenside striations in the QFV (Fig. 4B) and to the regional stretch lineation defined by Roberts et al. (1978) and Roberts (1981). Such elongated high-grade-ore zones are a common feature in Archean gold deposits (e.g., Andrews et al. 1986; Hodgson 1989; Tourigny et al. 1989).

**Timing of vein emplacement**

Foliated wall-rock inclusions in the QFV imply that quartz veining postdates the regional penetrative deformation. However, boudinaged and isoclinal folded veins in the wall rock (Fig. 5A), locally serrated contacts between the wall rock and the QFV (Fig. 5B), together with folding (Fig. 6A) of and recrystallization (Fig. 5F) in the QFV, indicate that some veining took place during deformation. Thus, the vein system was formed during progressive deformation in a dynamic tectonic environment. This conclusion is in agreement with previous studies in the Timmins camp by Piroshchko and Hodgson (1988) and by Roberts and Stevens (1989).

**Structural interpretation**

The formation of the ribbon-textured QFV striking parallel to the foliation, which is parallel to the XY plane of the finite-strain ellipsoid (Ramsay and Graham 1970; Ramsay 1980b) but dipping steeply opposite to the foliation (Fig. 4A), is compatible with the classical model for the genesis of Archean lode-gold deposits with reverse dip-slip faulting during simple shear (Robert and Brown 1986a; Sibson et al. 1988). Shear failure at a high angle to σ1 generated the QFV, and concomitant extensional opening in the σ1–σ2 plane, perpendicular to the slickenside striation in the QFV, resulted in the formation of the subhorizontal veins typically known as flats (Fig. 6B).

However, the highly variable orientation of many of the quartz veins in the wall rock adjacent to the QFV (Fig. 4C) is inconsistent with a plain model of progressive simple shear. It is likely that this diverse pattern of vein orientation results from two simultaneously operating processes: (i) The contact between slate and carbonatized komatiite represented a plane of anisotropy during compressive deformation where high strain was preferentially partitioned. Indeed, the foliation in the carbonatized komatiite becomes progressively better developed as the slate contact is approached. Thus, the quartz–fuchsite vein system was emplaced in an inhomogeneous environment with relatively massive carbonatized komatiite grading into a more foliated counterpart bounded by a slate unit. The compe-
Fig. 5. (A) Plane view of an isoclinally folded vein in the wall rock (a). The foliation (b) is axial planar to the fold of the vein in the wall rock. Note the discordant relationship between the quartz–fuchsite vein (QFV) (c) and the regional foliation (b). Scale bar = 20 cm. (B) Plane view of the serrated contact between the QFV and the wall rock (a). Note the fracture cleavage in the vein (b). c, foliation. Scale bar = 20 cm. (C) Plane view of the typical ore-bearing zone of the QFV. a, gold-bearing ribbon quartz; b, massive and barren quartz; c, boudinage of the ribbon quartz; d, crosscutting “ladder” vein. Scale bar = 50 cm. (D) Boudinage of the QFV with sigmoidal vein in the pinch of the boudinage structure (longitudinal vertical section). Scale bar = 50 cm. (E) Folding of ribbon-textured quartz (a) in the QFV. b, boudinage of the ribbon quartz; c, fracture cleavage; d, stylolitized phyllosilicate band (oblique plane view). Scale bar = 20 cm. (F) Typical crack-seal structure in the ribbon quartz of the QFV. a, phyllosilicate laminae in optical continuous quartz; b, inclusion trails in crystallographically continuous quartz; c, stylolite; d, recrystallized quartz. Scale bar = 0.2 mm.

Tendency contrast between these rock units must have generated strain refraction leading to the development of variably oriented fractures (Treagus 1988; Dubé et al. 1989; Poulsen and Robert 1989). This effect may have been accentuated once the QFV was formed and became part of the composite rock mass. (ii) Since the quartz–fuchsite vein system formed in a dynamic tectonic environment, changes in the intensity of the deviatoric stress are likely, and intermittent switches in the orientation of $\sigma_2$ and $\sigma_3$ may have occurred while $\sigma_1$ remained constant. Occasionally, $\sigma_2$ and $\sigma_3$ may have had similar intensities (see Fig. 8). Changes in deviatoric stress intensity can be accounted for either by the internal dynamic evolution of the fault–vein system during intermittent stress relaxation along the fault (Sibson et al. 1988) or by recurrent variations of the regional
Fig. 6. (A) Vertical section view of the folding of the quartz–fuchsite vein (QFV) indicating a reverse fault movement along the vein. Scale bar = 50 cm. (B) Vertical section view of a set of flats (a) opened normal to the QFV (b). The deflected attitude of the flats at the contact with the QFV indicates a reverse dip-slip movement along the latter. Scale bar = 50 cm. (C) Longitudinal section view of massive vertical veins (a) merging with the QFV (b). Scale bar = 50 cm. (D) Plane view of vertical veins (a) merging with the QFV (b). Scale bar = 1 m. (E) System of contemporaneous horizontal and subvertical veins in the wall rock immediately adjacent to the QFV (longitudinal section view parallel to the strike of the QFV). Scale bar = 50 cm. (F) Vertical section view of a set of sigmoidal en echelon veins (a) crosscutting a flat (b). Scale bar = 20 cm. See Fig. 4 for symbols in the stereographic projections.
stress regime. Thus, during periods of relatively high deviatoric stress with \( \sigma_1 \) vertical (Fig. 8B), shear failure occurred along the QFV with concomitant formation of the flats, whereas during intervals of relatively low deviatoric stress with \( \sigma_3 \) horizontal (Fig. 8C) vertical fracturing took place normal to the least principal stress and to the QFV, and possibly along rock anisotropies. The quartz veins in proximity to the QFV that have intermediate orientations between flats and subvertical veins probably occupy the continuum of fractures that may form when \( \sigma_2 \equiv \sigma_3 \). The horizontal veins connected by vertical veins (Fig. 6E) are good evidence for \( \sigma_2 \) being roughly equal to \( \sigma_3 \) at certain times. A similar scenario has been invoked by Kerrich and Allison (1978) to explain the vein geometry of gold-bearing veins in the Yellowknife greenstone belt, although they have advocated radical switches in the orientation of \( \sigma_1 \) and \( \sigma_3 \) within a static stress regime, and they did not consider the orientation of \( \sigma_2 \). Finally, it cannot be ruled out that veining occurred during more than one event of deformation, with a reorientation of the principal stresses, and that preexisting fractures unrelated to the stress conditions prevailing during formation of the QFV may have served as sites for veining.

The "ladder" veins within the QFV reflect a response to compressional deformation (Figs. 5C, 5D). The discordant veins in the QFV are akin to extensional fractures that form in anisotropic rocks (Platt and Vissers 1980). Limited extension along the QFV caused brittle failure of the banding and development of extensional and oblique fractures. These fractures probably acted partly as sinks for silica removed by pressure solution in the banding during progressive deformation. Shortening of the rock normal and oblique to the banding produced the pinch-and-swell structures (Figs. 5C, 5D).

A reverse oblique-slip motion along the QFV with a displacement vector plunging to the east is indicated by the orientation of the slickensides striations (Fig. 4B), stepped surfaces along the slickensides, deflection of the flats by movement along the QFV (Fig. 6B), vergence of folding in the QFV (Fig. 6A), and angle of the foliation with respect to the QFV. Roberts and Stevens (1989) have deduced a sinistral sense of shear movement along the zone of altered rocks hosting the QFV, which is not compatible with the orientation of the slickenside striations. This discrepancy is not resolved yet, but it may indicate that two kinematical events have been recorded in this area. Sagittal en echelon vein systems crosscutting flats and indicating a left-hand displacement (Fig. 6F) may belong to the sinistral shearing event described by Roberts and Stevens (1989).

**Mechanism of vein formation**

The presence of wall-rock breccia embedded in quartz and the widespread occurrence of extensional veins formed in the compressional stress environment applicable to the QFV indicates a regime of high pore-fluid pressure and suggest that the vein system was essentially emplaced in hydraulically induced fractures (Phillips 1972; Fyfe et al. 1978; Cox et al. 1987). High pore-fluid pressures were partly the consequence of the intense carbonate alteration of the host komatiite whereby the volume of the rock increased with a concomitant drop in bulk-rock permeability (cf. Kerrich 1983; Kishida and Kerrich 1987). It is the combination of the regional compressive stress and the syntectonic alteration of the host rock that created the necessary requirements for veining formation. At high deviatoric stress conditions, fracturing occurs by shear failure, whereas extension fractures form at low deviatoric stress conditions when the fluid pressure exceeds the least principal stress by an amount greater than the tensile strength of the rock \( (P_f > \sigma_3 + T) \) (Yardley 1986; Cox et al. 1987). In the present case, veining took place along shear fractures, e.g., QFV, and along extensional fractures, e.g., flats and vertical veins. Some extensional hydraulic fracturing was probably also controlled by the rock anisotropy or by preexisting fractures (cf. Haimson 1981; Cornet 1982).

The presence of contemporaneous massive and ribbon quartz in the quartz–fuchsite vein system is indicative of two different alternately operating mechanisms of vein formation. On the one hand, massive quartz veins and lenses usually form during a prolonged stage of fracture growth and opening associated with continuous crystallization. As long as the fluid pressure within the fracture is sufficiently high to hold the vein walls apart \( (P_f > \sigma_3) \) and the fluid remains supersaturated in certain components, vein growth will persist. The vein seals once the fluid pressure drops below the normal stress acting on its walls \( (P_f < \sigma_3) \), or when mineral growth is faster than the rate of fracture-wall separation (Cox et al. 1987). On the other hand, the ribbon quartz with the characteristic crack-seal microstructure (Fig. 5F) involves many repeated increments of microcrack opening either by shear slip or by pure extension, followed by sealing due to crystallization of material from solution (Ramsay 1980a; Cox and Etheridge 1983; Ramsay and Huber 1983; Cox 1987; Mawer 1987). The high Cr, Ni, and Ir abundances in fuchsite and chlorite separates from the ribbons are evidence that these represent cleaved komatiite wall-rock selvages (Moritz 1988). Each crack-seal increment is accompanied by an instantaneous drop in fluid pressure inside the fracture with respect to the surrounding rock, resulting in fluid migration into the crack until fluid pressure is reequilibrated (Fyfe et al. 1978; Etheridge et al. 1984). Once this stress state is obtained, the crack seals.

As pointed out above, the lack of a distinctive alteration envelope around the QFV suggests the vein was formed by an essentially rock-equilibrated fluid. Thus, it is likely that a part of the fluid migrating into the open crack during each fracture increment diffused out of the surrounding wall rock. The drop in fluid pressure inside the crack is small with respect to the total...
Fig. 8. Variations in principal stresses with depth (after Means 1976; Brisbin 1986). (A) Simple lithostatic case in the absence of any deviatoric stress. The least principal stress is horizontal for any given depth. (B) Lithostatic stress conditions in the case of a northwest–southeast-directed horizontal tectonic compression and high deviatoric stress. At shallow depth, the least principal stress is vertical ($\sigma_3 = \sigma_V$), whereas deeper in the crust the least principal stress becomes horizontal ($\sigma_3 = \sigma_{HNE-SW}$). The critical depth is where $\sigma_3 = \sigma_V = \sigma_{HNE-SW}$. (C) Same as for B but for low deviatoric stress conditions. Note how the critical depth becomes shallower as the deviatoric stress is released. (D) Preferred vein orientation under deviatoric stress conditions. At shallow depth, where $\sigma_3 = \sigma_V < \sigma_{HNE-SW}$, veins will be horizontal, whereas at greater depth, where $\sigma_V > \sigma_{HNE-SW} = \sigma_3$, veins will be vertical. At the critical depth, $\sigma_3 = \sigma_V = \sigma_{HNE-SW}$, veins will occupy vertical and horizontal planes, as well as intermediate orientations. The orientation of the maximum principal stress is northwest–southeast, and the fault plane indicates the position of the quartz–fuchsite vein. The vein geometry of the quartz–fuchsite vein system suggests that the latter was emplaced at a critical depth, with $\sigma_V$ being both vertical and horizontal, or that the intensity of the deviatoric stress was variable during vein formation, i.e., conditions were changing intermittently from B to C and vice versa.

Fluid pressure in the enclosing rock. Consequently, only those minerals whose solubilities are strongly pressure sensitive precipitate (Hobbs 1987). Quartz, the main vein constituent, is such a mineral (Walther and Helgeson 1977; Fournier 1985).

As the fracture system spread out during deformation and vein formation, it probably became a very efficient drain for pumping fluids from depth (cf. Yardley 1986; Sibson et al. 1988). The fuchsite–pyrite alteration around the QVF at shallow depth (6th and 8th levels) with economic gold concentrations in the adjacent wall rock, a feature which is anomalous relative to much of the QVF extension, may reflect such a pumping mechanism. A likely scenario is that at depth fluid pressures were lower than lithostatic pressure and fluids tended to migrate into the fracture system, whereas at the top of the fracture system fluid pressures exceeded lithostatic pressure and the fluids tended to move out of the fracture system to form the fuchsite–pyrite halo and to deposit gold in the wall rock adjacent to the QVF (Fig. 9).

Relationship between gold deposition and vein formation

Gold was most certainly introduced into the QVF along with the bulk of quartz, rather than selectively into the ribbon quartz after deposition and deformation of the vein system. Quartz recrystallization and stylolites are common in ribbon quartz (Fig. 5F), whereas massive quartz more commonly exhibits a fracture cleavage (Fig. 5B). The mylonitic texture of the ribbon quartz reflects a plastic deformation (White et al. 1980) which typically causes a substantial decrease in permeability (Brace 1968, 1980), whereas the massive quartz texture indicates mainly a brittle deformation which results in an increase in permeability (Brace and Orange 1968). Thus, if the gold-bearing fluid was introduced in the QVF after quartz deposition and deformation, fluid flow should have been largely confined to the massive unbanded zones of the QVF, as the reduction of permeability in the ribbon quartz would have inhibited fluid motion. Consequently, deposition of gold should have taken place primarily in the massive unbanded domains of the QVF rather than in the ribbon quartz. However, the gold distribution in the QVF reflects just the opposite pattern. Thus, introduction of gold during vein formation appears to be the more likely scenario.

The systematic affinity of high gold grades for the ribbon quartz suggests a genetic relationship. This type of quartz veining seems to be very productive in many other vein-type gold deposits (Malcolm 1929; Chace 1949; McKinstry and Ohle 1949; Covension 1981; Groves et al. 1985; Read and Meinert 1986; Robert and Brown 1986b; Vearncombe 1986; Cox et al. 1987; Mawer 1987; Tomlinson et al. 1988). In many cases, ore grades are directly related to the abundance of such ribbon quartz. In the QVF, multiple crack-seal vein growth must have
been a very effective mechanism for removing gold and associated elements from the ore-bearing fluid. Gold was likely deposited from a hydrothermal fluid which, like silica, was very sensitive to slight pressure variations. Indeed, a microthermometric fluid inclusion investigation indicates that intermittent unmixing of an H₂O-CO₂-dominated fluid took place in the QFV, which was likely induced by slight pressure drops accompanying the crack-seal mechanism of veining (Moritz 1988; Moritz and Crocket 1989). Losses of CO₂ and other reduced gas species to the vapor during such phase separation have the effect of increasing the pH and the fO₂ of a hydrothermal fluid (Drummond and Ohmoto 1985), which in turn directly mediate the solubility of gold under hydrothermal conditions (Seward 1984; Shenberger and Barnes 1989).

Conclusions

The quartz–fuchsite vein system was emplaced in a dynamic tectonic environment during a progressive compressional deformation event which imparted the regional foliation to the host rocks. The favorable requirements for vein formation were created by the combination of the regional stress regime, the syntectonic alteration of the host rocks, and the contact between a slate unit and komatiite flows which acted as a plane of anisotropy along which strain was partitioned during progressive deformation. In the main, the geometry of the vein system can be attributed to reverse oblique-slip faulting during simple shear, as is established in other Archean lode-gold deposits. In detail, however, the anatomy of the vein system is more complex, probably due to intermittent variations of the deviatoric stress regime, strain refraction, and reactivation of pre-existing structures. The difficulty of resolving the geometry of the quartz–fuchsite vein system by simple shear analysis may partly explain differing genetic models for vein-type gold mineralization in the Timmins camp, and at the Dome mine in particular, where gold-bearing veins occur in a great variety of lithological and structural settings.

Quartz deposition took place in hydraulically induced fractures under a high pore-fluid pressure regime. Massive and barren quartz was deposited during prolonged episodes of simple vein growth, whereas gold-bearing ribbon quartz was precipitated in the course of repetitive and brief periods of crack-seal vein growth. Gold deposition is attributed to the small pressure drops that commonly accompany the crack-seal vein growth mechanism. A literature survey suggests that the genetic affinity of crack-seal vein growth and high gold grades is quite common and indicates that ribbon-textured quartz veins are excellent targets for exploration for high-grade gold mineralizations.

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