Geometric aspects of a large extensional vein, Donalda deposit, Rouyn-Noranda, Quebec

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Abstract: The Donalda gold deposit in the Noranda district of the Abitibi belt is an unusually extensive shallow-dipping quartz vein covering nearly 0.5 km^2. A detailed structural analysis of the vein shows that it consists of dominant shallowly south-dipping arrays of extensional veins, moderately south-dipping, east-west reverse shear zones, and a poorly developed conjugate set of north-dipping reverse shear zones. Local continuity of vein quartz between the three types of structures indicates their contemporaneity. The shallow-dip arrays consist of overlapping first-order extensional veins linked by moderately dipping second-order extensional veins; the shallow-dip arrays are interpreted as "extensional" arrays formed perpendicular to the minimum external strain axis. The kinematics and nature of the different structures indicate that the Donalda deposit formed as a result of north-south shortening and subvertical elongation, common to many gold-quartz vein deposits in southern Abitibi belt.

Résumé : Le gisement d'or de Donalda du district de Noranda dans la ceinture de l'Abitibi consiste en une veine de quartz à pendage faible, couvrant près de 0,5 kilomètre carré, ce qui est rare pour une telle entité. Une étude structurale détaillée a montré que la veine se compose principalement de segments à pendage faible vers le sud, constitués de veines d'extension, mais aussi de zones de cisaillement inverse d'orientation est-ouest à pendage modéré vers le sud et d'un jeu conjugué faiblement développé de zones de cisaillement inverse à pendage modéré vers le nord. Une continuité locale du quartz entre les veines des trois types de structures atteste de leur contemporanéité. Les segments à pendage faible combinent plusieurs veines d'extension de premier ordre disposées en relais, reliées par des veines d'extension de deuxième ordre à pendage plus fort; ces segments à pendage faible représentent des structures en extension formées perpendiculairement à l'axe externe d'allongement. La cinématique et la nature des différentes structures indiquent que le gisement de Donalda s'est formé par raccourcissement nord-sud et allongement subvertical, comme c'est le cas de nombreux gisements d'or filonien de la partie sud de la ceinture de l'Abitibi.

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INTRODUCTION

Extensional veins are common components of shear-zone-related quartz-carbonate vein networks (Hodgson, 1990; Robert, 1990). In most cases, they are subhorizontal and fringe laminated fault-fill veins occurring in the central parts of moderately- to steeply-dipping reverse shear zones. Extensional veins are components of arrays at the lateral, up- and down-dip terminations of fault-fill veins, or of planar tabular bodies extending in low strain rocks away from fault-fill veins over significant distances (Robert, 1990). In the latter case, veins may occur over large areas, either as continuous single bodies or as combinations of distinct, overlapping, and interconnected segments.

Such tabular subhorizontal extensional veins developed in greenschist grade rocks during crustal shortening have also been used as evidence for lithostatic fluid pressures at mid-crustal levels (Sibson et al., 1988; Sibson, 1990). Thus, understanding their detailed geometry and mode of propagation also has bearing on the phenomenon of fluid overpressures and on the scale at which it may occur.

This note presents the preliminary results of a structural analysis of a large, shallow-dipping extensional vein at the Donalda deposit near Rouyn-Noranda, Quebec, described by Riverin et al. (1990). This vein covers an area of approximately 0.5 km^2 and is well exposed on walls and pillars of accessible mine workings. It provides a unique opportunity to examine the detailed geometric configuration of the vein and its relations with moderately dipping shear zone-hosted veins.

GEOLOGY OF THE DONALDA DEPOSIT

The geology of the Donalda deposit has previously been described in detail by Riverin et al. (1990), and only the key points are presented here. The deposit occurs in the southern part of the Noranda mining camp, less than 1 km northeast of the town of Rouyn-Noranda (Fig. 1). It straddles the contact between two volcanic formations separated by the Horne Creek fault, a major fault striking east-west and dipping 70° to the north. The Quemont rhyolite occurs on the north side of the fault and the Wilco andesite to the south. The deposit comprises two auriferous quartz veins, dipping shallowly (No. 1 vein) to moderately (No. 2 vein) to the south (Fig. 2). The No. 1 vein contributed the bulk of the ore and was the only vein accessible during the present study. This vein cuts both the Wilco andesite and the Quemont rhyolite, but is offset by the Horne Creek fault. Both volcanic formations and the No. 1 vein are cut by the D'Eldona diabase dyke, striking east-northeast and 20 m thick; the diabase dyke is also offset by the Horne Creek fault (Fig. 1, 2). The Donalda deposit also occurs in proximity to the Horne and Quemont auriferous volcanic-associated massive sulphide (VMS) deposits (Fig. 1)

The No. 1 vein strikes east and has an overall dip of 20° to the south. As shown in Figure 1, the vein occurs on both sides of the Horne Creek fault, covering a minimum area of 0.5 km^2, over which its thickness averages 20-30 cm. As described by Riverin et al. (1990), it consists of alternating moderately-dipping and dominant shallowly-dipping mineralized vein segments (Fig. 2), the latter being fringed by common low-angle splays. The vein and its numerous splays have sharp planar walls and are internally banded parallel or subparallel to their walls.

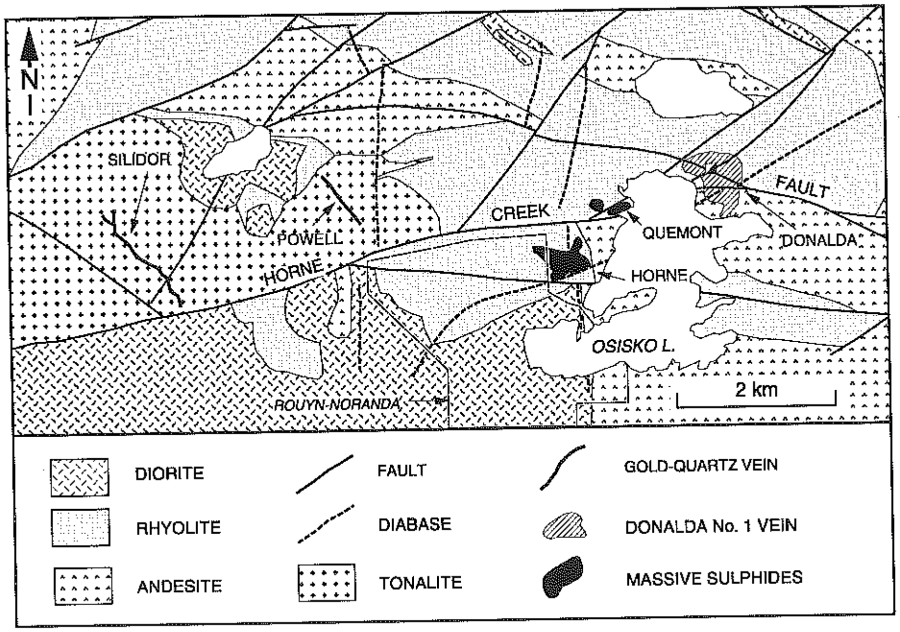

Figure 1. *Simplified geological map of the Noranda area, showing the surface projection of the Donalda and other nearby base metal and gold deposits. Modified from Riverin et al. (1990).*

GEOMETRIC ELEMENTS OF THE NO. 1 VEIN

At the mine scale, the geometry of the No. 1 vein is defined by alternating vein segments of shallow and moderate dips to the south (Riverin et al., 1990). The shallowly dipping segments are more extensive than the moderately dipping ones, resulting in a stepped vein with an overall dip of 20° to the south (Fig. 3A). By virtue of their more restricted dimensions, the moderate-dip segments form relays between larger shallow-dip segments. As illustrated in Figure 3, this type of pattern is observed at kilometre to metre scales.

The shallow-dip segments of the No. 1 vein in turn comprise two sets of connected extensional veins: "first-order" veins, the most extensive ones, fringed by "second-order" veins of more restricted dimensions (Fig. 4A). The first-order veins are relatively continuous and form an array of overlapping veins parallel to the shallow-dip segments in which they occur. Second-order veins have varied dimensions and orientations; they form a series of splays branching off the first-order veins and linking them in relay zones (Fig. 4). Our observations suggest that, in contrast, the moderate-dip segments of the No. 1 vein contain very few, if any, second-order veins. In many cases, the arrangement of first- and second-order veins in shallow-dip segments of the No. 1 vein is very similar to that observed at the mine scale (Fig. 3, 4), suggesting a fractal character of the geometry of the vein.

In addition, a small number of vein-bearing, moderately north-dipping shear zones were recognized as geometric elements probably related to the No. 1 vein. In the following paragraphs, we describe successively the detailed geometry of shallow-dip and moderate-dip segments of the No. 1 vein and their main components, followed by that of the moderately north-dipping shear zones.

Shallow-dip vein segments

As indicated above, each significant shallow-dip segment of the No. 1 vein consists of a number of first-order veins, generally subparallel to the segment but of slightly different orientations, linked to each other by second-order veins.

First-order veins

First-order veins in shallow-dip segments vary in dip from 10 to 40° to the south and range in strike from 025 to 140° (Fig. 5A). Their average orientation is 090-20° (right-hand rule), parallel to the average orientation of shallow-dip segments (Riverin et al., 1990). In a given local area of the mine, the first-order veins show a consistent parallel orientation. However, other areas of the mine are characterized by slightly different orientations of first-order veins, which may correspond to independant vein segments propagating in slightly different directions (see below). First-order veins range in thickness from 10-100 cm, and their dip lengths generally exceed 5 m.

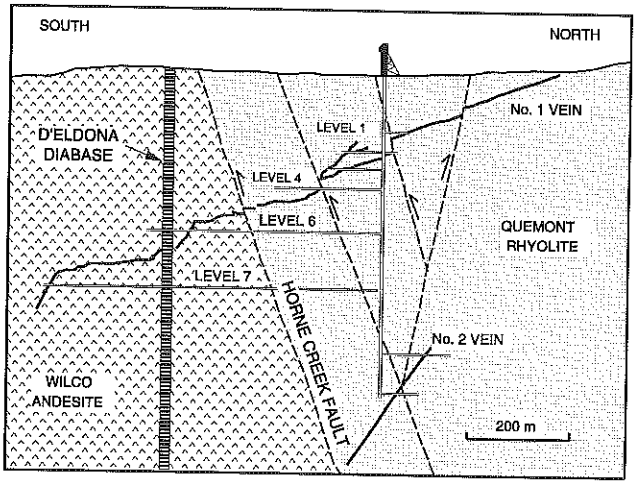

Figure 2. Geological north-south cross-section through the shaft of the Donalda deposit. Adapted from Riverin et al. (1990).

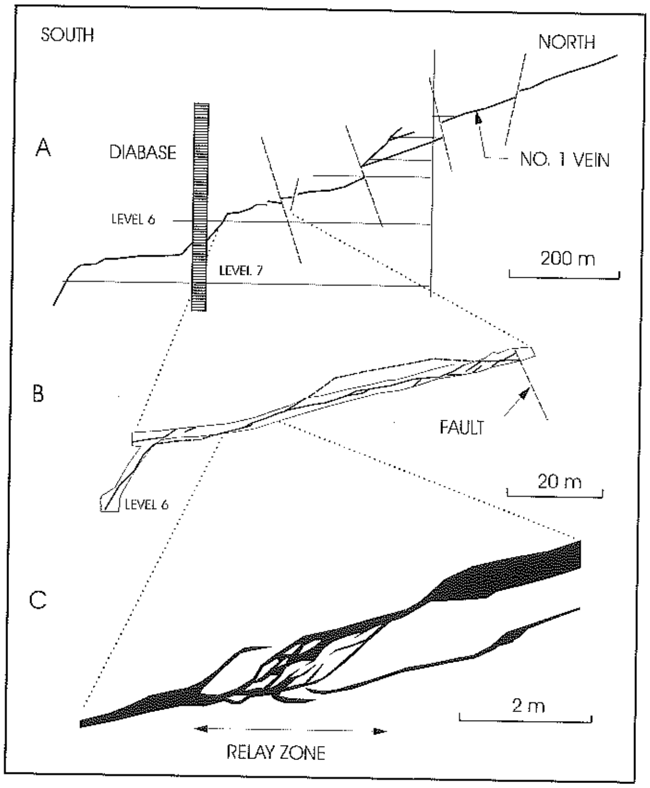

Figure 3. Geometry of the No. 1 vein at different scales as seen on north-south cross-sections. ***A)*** *Simplified cross-section through the shaft, modified from Figure 2.* ***B)*** *Cross-section showing details of a shallow-dip segment of the vein.* ***C)*** *Detail of the relay zone between two first-order veins.*

Second-order veins

Second-order veins are all systematically linked to first-order veins. They are generally planar (Fig. 4B), but in a few areas they have clear sigmoidal shapes (Fig. 4C). Second-order veins are typically less than a few tens of centimetres thick and their continuity along the dip is less than a few metres. Although they occur both in the hangingwalls and footwalls of dilatant en échelon first-order veins, second-order veins do not have a uniform distribution: they are more abundant in relay zones at the terminations of en échelon first-order veins.

In most cases, intersections between first- and second-order veins do not show crosscutting relationships but rather quartz is continuous beween the two vein orders. Furthermore, in a number of cases, the total vein thickness remains approximately constant in the transition from a single first-order vein to a relay area containing mostly second-order veins, as is the case in Figure 4C. Such relationships suggest that each second-order vein represents an increment of development of the first-order vein.

In north-south cross-section, second-order veins display a range of angular relations with the first-order veins. They have dips that are either shallower, or more commonly steeper, than those of first-order veins, and in some cases dips in the opposite direction (Fig. 4A, 5A). Second-order veins have the same range of strikes as the first-order veins, and their dips vary between those of first-order veins in shallow- and moderate-dip segments of the No. 1 vein (Fig. 5A). A significant number of second-order veins are in fact parallel to the moderate-dip first-order veins, suggesting that moderate-dip segments of the No.1 vein may in fact be well developed equivalents of second-order veins.

As discussed below, the intersections between pairs of first- and second-order veins may yield information on the propagation directions of the vein segments. We have therefore measured wherever possible, but most commonly calculated, the orientations of intersections between such pairs of

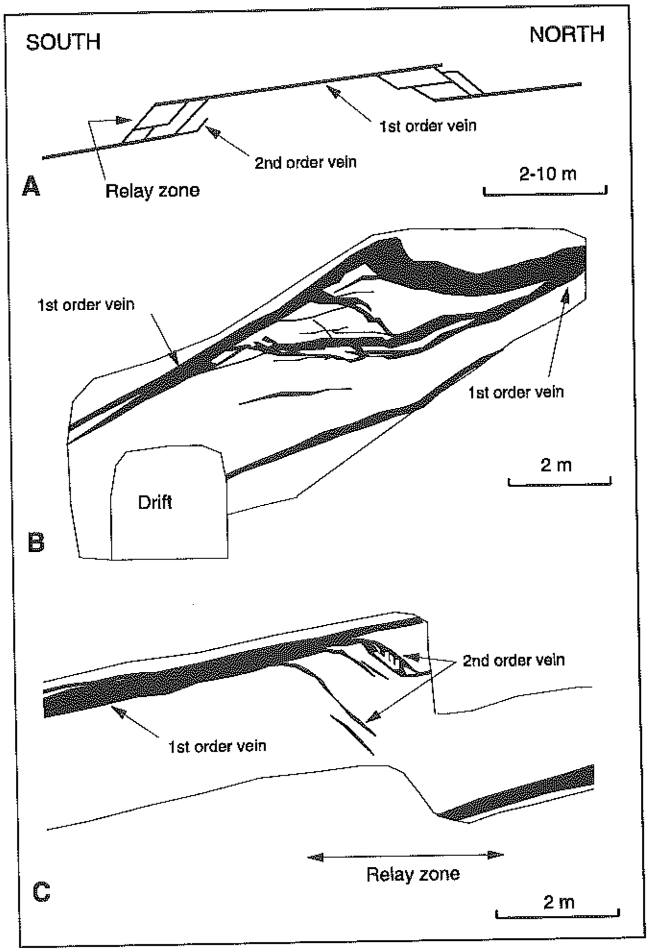

Figure 4. Geometric relations between first- and second-order veins in shallow-dip segments of the No. 1 vein. A) Schematic representation of observed elements and their relationships. B) Relay zone showing abundant, relatively planar second-order veins between two first-order ones; Level 2. C) Sigmoidal second-order veins in a relay zone; slightly above Level 1.

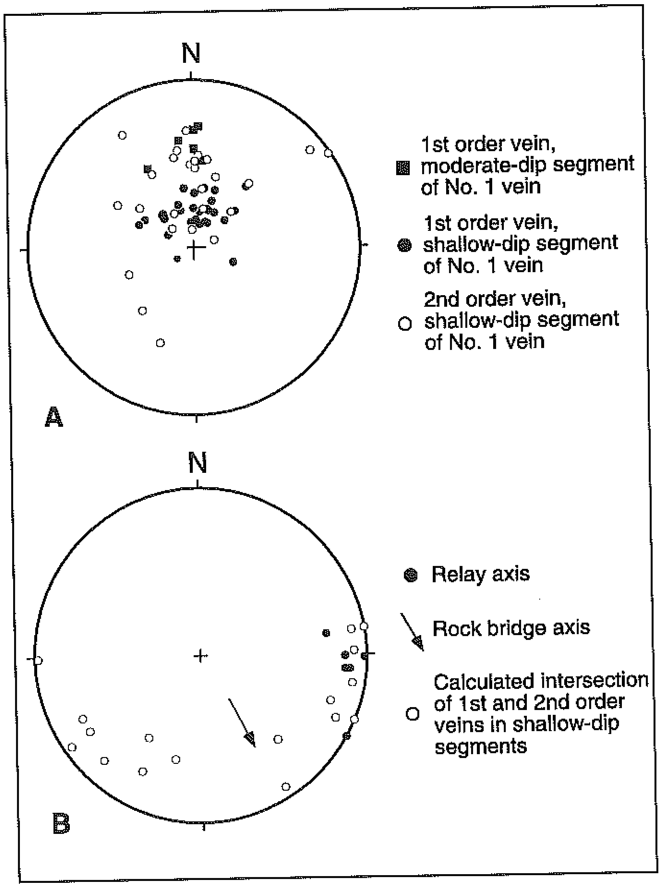

Figure 5. Stereographic projections of structural elements of the No. 1 vein, equal area, lower hemisphere. A) Poles to first- and second-order veins in shallow-dip segments and to first-order veins in moderate-dip segments. B) Vein intersections and other linear elements of the veins.

veins. The intersections between pairs of first- and second-order veins have shallow plunges and are grouped around two main directions: 090° and 225° (Fig. 5B). However, one should keep in mind that calculated intersections are in most cases less accurate than ones that have been measured directly. The 090° intersections are also parallel to measured axes of relay zones between overlapping first-order veins (see below).

Relay zones between first-order veins

Relay zones of variable sizes have been observed at several localities between dilatant first-order veins in shallow-dip segments. The vertical spacing between adjacent overlapping first-order veins ranges from a few tens of centimetres (Fig. 3C) to a few metres (Fig. 4C). The first-order veins show limited overlap (Fig. 3C, 4C), and they are typically connected by a network of second-order veins. They grade into incipient breccias where these linking second-order veins are particularly abundant (Fig. 3C).

The axes of a number of relay zones have been measured directly (e.g. Fig. 6). They mainly trend east-west and have subhorizontal plunges (Fig. 5B), parallel to one of the groups of intersections between first- and second-order veins. The relay zones do not present any systematic sense of stepping along a given shallow-dip segment of the No. 1 vein. Both upward steps (Fig. 3C, 6) and downward steps (Fig. 4C, 6) were observed, but upward steps must dominate, given the overall 20° dip to the south of the shallow-dip segments.

Moderate-dip vein segments

Our observations indicate that moderate-dip segments of the No. 1 vein are composed of single continuous first-order veins, a few tens of centimetres thick, with very few, if any, fringing second-order veins. The first-order veins dip moderately to the south (Fig. 2) and have a relatively constant orientation of 090-50° (Fig. 5A)

Intersections between shallow-dip and moderate-dip segments of the No. 1 vein have only been observed at one locality. Here, first-order veins of both segments are simply continuous into one another, without any apparent discontinuity, indicating that they are contemporaneous. This is similar to the relation observed between first- and second-order veins in shallow-dip segments.

In the Wilco andesite, the walls of moderate-dip vein segments are moderately foliated over a few tens of centimetres, in contrast to those along shallow-dip segments. Some foliation planes contain striations with a steep rake to the west. In thin section cut perpendicular to foliation and parallel to striations, well-developed "C-S" structures indicate reverse movement along the vein walls (Fig. 7).

Moderate-dip shear zones

Vein-bearing shear zones, not previously documented, have been observed at two localities. They strike east-west, dip 50-65° to the north, and are 0.5-1.0 m thick. These shear zones are defined by well-developed foliation, subparallel to their

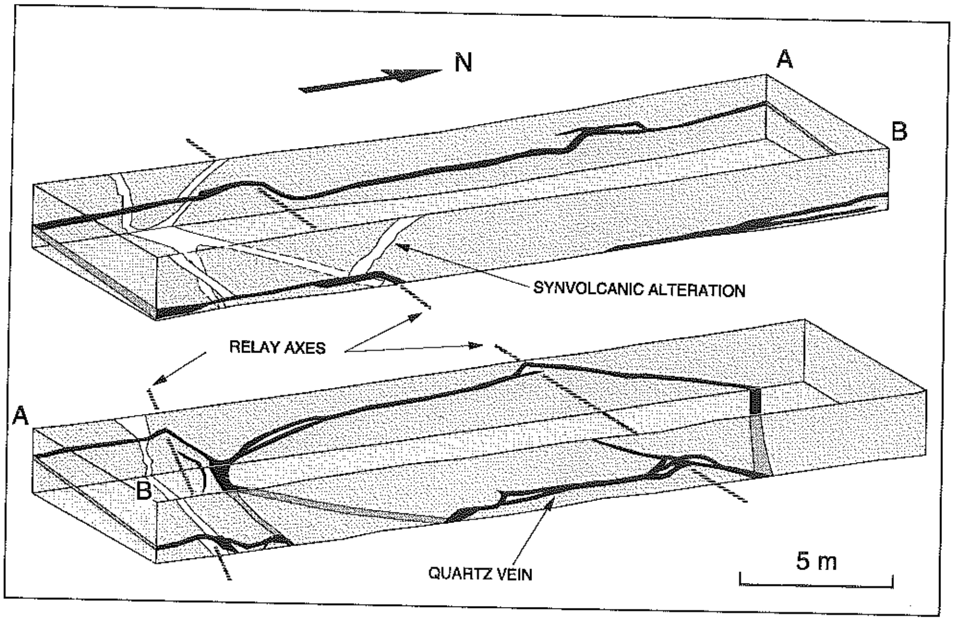

Figure 6. Three-dimensional representation of a portion of a shallow-dip vein segment mapped in detail. It shows the geometry of the vein, axes of relays, and offsets of synvolcanic alteration bands along the vein; low-angle raise above Level 7.

envelope, and they contain massive to laminated central, fault-fill veins. In both cases, down-dip striations on foliation planes indicate that vertical movements took place along the shear zones. In one case, the obliquity of the foliation with the shear zone boundary indicates reverse movement (Fig. 8). It is not clear how much of the total reverse vertical offset of the No. 1 vein is related to the shear zone, to the overprinting gougy fault (Fig. 8), or both. In the other case, deflection of the No. 1 vein indicates reverse movement in the order of a few metres. Besides the late structural complications, these north-dipping shear zones are similar in many respects to auriferous ones present in many other deposits in the Abitibi greenstone belt (Robert, 1990).

The age relationships observed between the No. 1 vein and the moderately north-dipping shear zones are different at the two locations. In one case (Fig. 8), the No. 1 vein segment in the footwall of the shear zone clearly cuts the foliation and merges without discontinuity with the vein central to the shear zone. Such relations suggest that the No.1 vein and that in the shear zone are contemporaneous and have formed during or after shear zone development. At the other location, the shear zone and its central laminated quartz vein cut and offset the No. 1 vein.

The conflicting crosscutting relationships documented between the No. 1 vein and the two north-dipping shear zones can be interpreted to indicate broadly coeval development of the two types of structures but the number of observations is rather limited. The continuity of vein quartz between the two types of structures provides a stronger case for this interpretation.

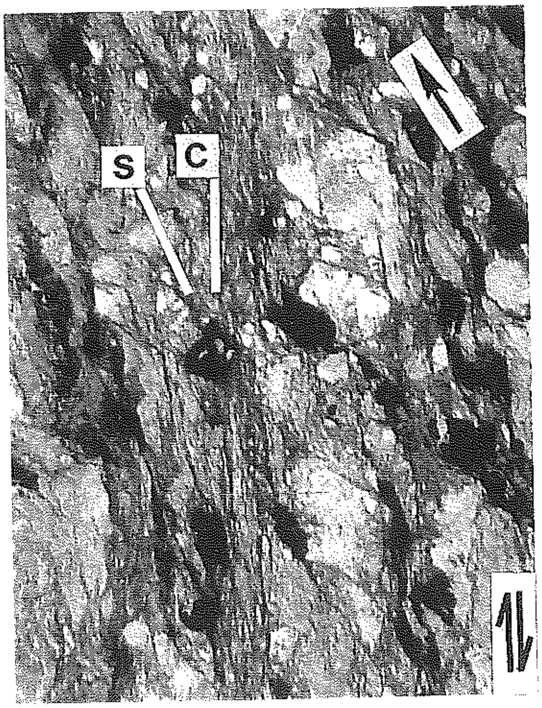

Figure 7. Photomicrograph of foliated wallrocks adjacent to a moderate-dip vein segment (Level) looking west, showing "C-S" structural fabrics; Level 6. Double arrows indicate the inferred sense of shear; the single arrow points to the top of the sample. Photo is 3.4 mm wide.

INTERNAL STRUCTURE OF THE NO. 1 VEIN

Internal structures and textures of vein yield important information on the details of vein development. Preliminary mesoscopic and microscopic observations and their implications are presented here.

Rock bridges

Rock bridges are a common feature of extensional veins: they consist of elongate bands of wallrock separating en échelon extensional veins which can be incorporated as oblique fragments within the veins (Pollard et al., 1982; Foxford et al., 1991). Rock bridges result from local stress perturbations at the tip of a propagating extensional fracture, and their long axes are parallel to the local propagation direction of the fracture (Foxford et al., 1991). The long axes of only two rock bridges could be determined; they trend at 150° (Fig. 5B).

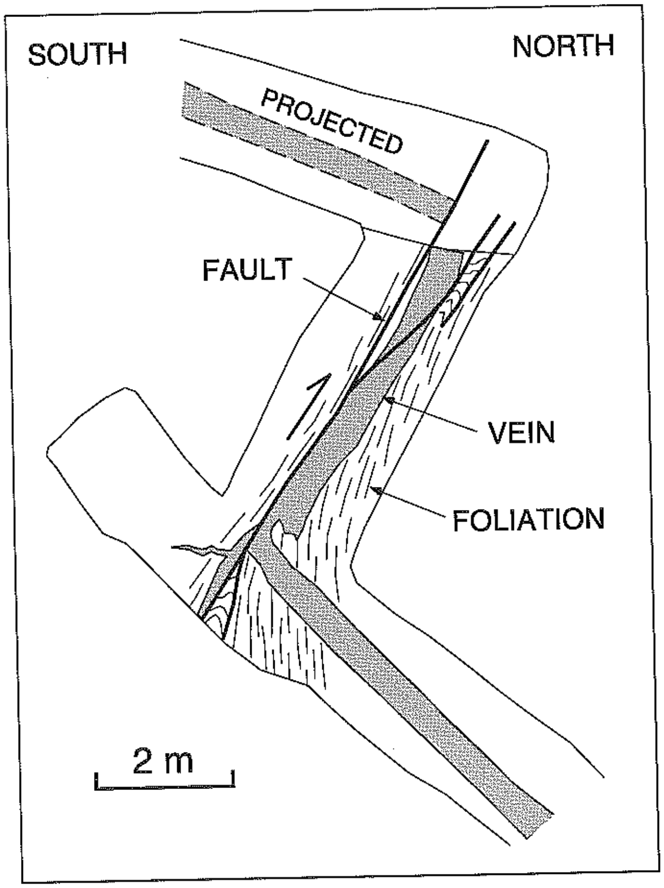

Figure 8. Detailed sketch of the intersection between a moderately north-dipping shear zone and the No. 1 vein; slightly below Level 3.

Internal layering

A dominant feature of both shallow-dip and moderate-dip vein segments is their internal layering. It is defined by alternating 1-10 cm thick layers of milky massive quartz, comb quartz and laminated quartz characterized by abundant millimetre-scale grey quartz laminae (Fig. 9). The layering is parallel to subparallel to the vein walls and is best developed in the shallow-dip vein segments. Such layering results at least in part from incremental vein growth (Fig. 9A).

Comb quartz layers are relatively common in shallow- and moderate-dip segments of the No. 1 vein. They consist of centimetre-scale, euhedral quartz crystals showing internal growth zones, at high angle to the walls of the vein or of their host layer (Fig. 10) and indicative of open-space filling. The interstices between crystals are filled with very fine grained quartz, accompanied by small amounts of chlorite, sericite, pyrite, tellurides, and gold. The coexistence of comb and very fine grained quartz in these layers probably results from sharp variations in precipitation rates, and fluid pressure variations provide on possible explanation for these contrasting textures.

Grey quartz laminae, which locally truncate quartz crystals, consist of angular clastic quartz embedded in a matrix of very fine grained quartz. They are generally parallel to the vein walls but may also dip moderately to the east (Fig. 9B), in which case small, top-to-the-west movements are indicated by offsets of other laminae. The fine grained quartz in such grey laminae does not display any preferred lattice orientations as it should if it originated by plastic deformation and dynamic recrystallization of larger quartz crystals. Although the presence of angular clastic quartz along the laminae probably reflects cataclastic processes, the very fine grained quartz matrix is best explained in the same way as the fine grained quartz interstitial to comb quartz crystals.

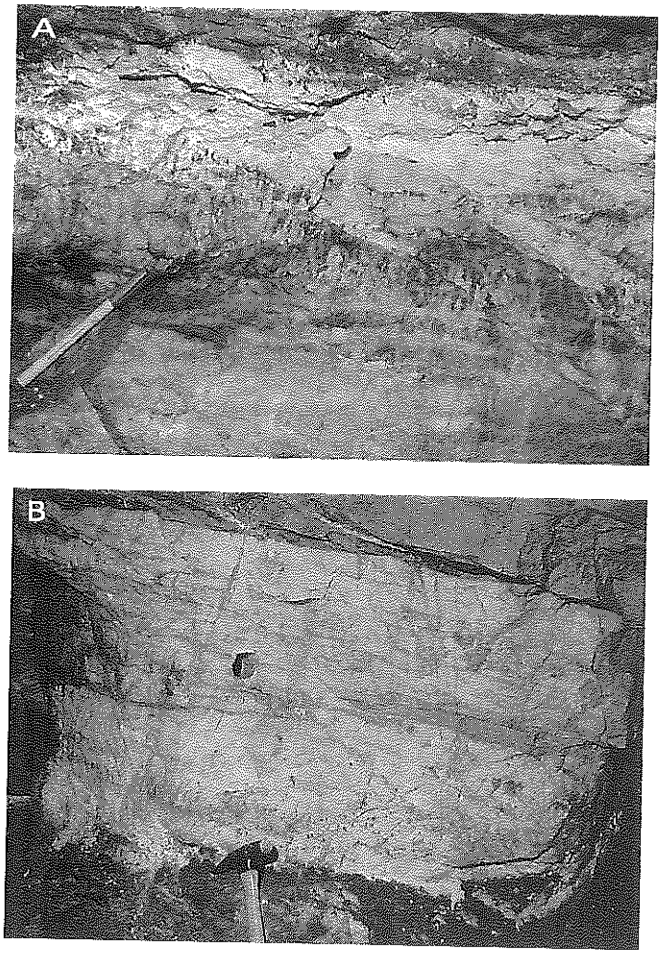

Figure 9. Details of internal layering of first-order veins in shallow-dip segments. A) Massive and comb quartz layers; note thin massive quartz layers cutting comb quartz in the lower part of the vein; above Level 1. View looking east; 20 cm long pen for scale. B) Laminated and massive quartz layers, above Level 1. View looking north; hammer for scale. Note east-dipping shear fractures cutting the layering in both A and B.

Movements along the vein

Two broad sets of striations have been observed along the walls of the No. 1 vein: a southerly trending set (190-220°) indicating dip-slip, north-south movements, and a westerly trending set (250-290°) indicating lateral movements. Dip-slip striations are best developed along the moderate-dip segments of the No. 1 vein where they rake steeply to the west, consistent with the reverse movements indicated by "C-S" structural fabrics. Similar striations occur locally in shallow-dip segments on the walls of first- and second-order veins, along which small reverse slips are indicated by offsets of truncated veins. Such dip-slip movements are likely related to the vein development history.

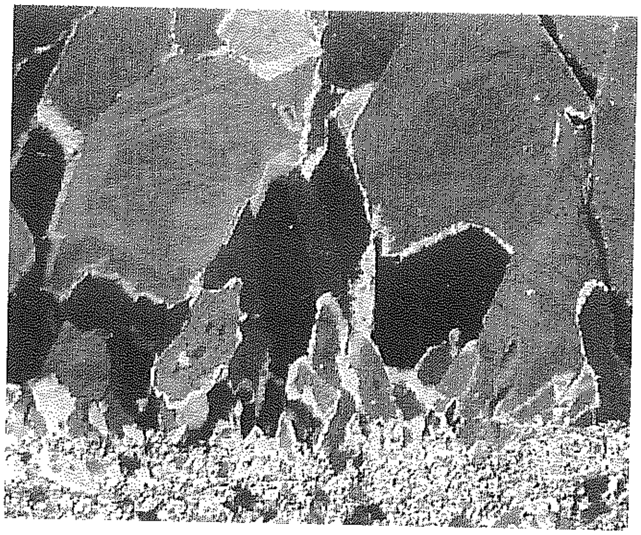

Figure 10. Photomicrograph showing details of comb quartz developed on a lamina of microcrystalline quartz. Width of photo is 3.8 mm.

The lateral movements indicated by the second set of striations have a top-to-the-east sense of slip based on offsets of a pair of divergent, pre-vein synvolcanic quartz-epidote alteration bands (Fig. 6, upper left). In contrast, the east-dipping reverse shear fractures observed within the veins (Fig. 9B) indicate thrusting to the west. The significance of such complex east-west movements is not understood, but some reactivation of the No. 1 vein may have occurred during late movements along the Horne Creek fault.

The opening vector along the various segments of the No. 1 vein could not be determined due to the absence of mineral fibres and to complicating effects of late lateral slip along the vein walls. However, despite minor lateral offsets along the vein, the synvolcanic alteration bands described above (Fig. 6) match relatively well above and below the vein. Such a close match suggests that the opening vector must be nearly perpendicular to the vein and precludes any significant north-south thrusting along it.

INTERPRETATIONS

Structural interpretation of the No. 1 vein

Several new observations support the interpretation of Riverin et al. (1990) that the No. 1 vein is largely an extensional vein, as opposed, for example, to a vein occupying a low angle thrust. In shallow-dip segments, individual first- and second-order veins have many attributes of extensional veins: planar walls, matching wall irregularities and rock bridges.

As described above, shallow-dip segments consist of overlapping first-order veins which in fact represent arrays of en échelon veins. An important question to address in restoring related strain axes is whether such an array is an extensional or a shear structure. The arrays defined by the first-order veins have the characteristics of "extensional arrays" as defined by Rothery (1988), in which extensional veins are at a very low angle to the array and show limited overlap, as opposed to those of "shear arrays" in which veins lie at higher angles to the array and show significant overlap. Extensional arrays are interpreted as forming perpendicular to the external extension or minimum strain direction (Rothery, 1988), in contrast to shearing arrays which form at an angle to the external shortening or maximum strain direction. Thus at Donalda, the shallow-dip segments of the No. 1 vein are interpreted as extensional arrays perpendicular to the minimum external strain direction (X), as shown in Figure 11. This interpretation is further supported by the fact that the first-order veins defining the array display relay zones of opposite sense in cross-section (Fig. 4A, 6) and by the lack of significant offset of synvolcanic alteration bands (Fig. 6), both of which are incompatible with reverse shearing along the shallow-dip segments.

As indicated above, moderate-dip segments of the No. 1 vein occupy south-dipping reverse shear zones. The veins themselves within these segments are well laminated and contain slivers of foliated wallrocks, as is typical of fault-fill veins (Robert et al., 1994), but the presence of comb quartz layers within them also indicates significant dilation during vein formation. The moderately north-dipping reverse shear zones also contain fault-fill veins, some of which are continuous with shallow-dip segments of No. 1 vein (Fig. 8). The continuity of veins observed between shallow-dip segments and the north- and south-dipping shear zones suggests that the three types of structures are broadly contemporaneous. The north- and south-dipping shear zones can thus be regarded as conjugate reverse shear zones, reflecting north-south, subhorizontal maximum shortening direction (Z) and vertical minimum shortening direction (X), compatible with the orientation of shallow-dip segments of the vein (Fig. 11). All three types of structures are compatible with their development in a north-south compressional regime.

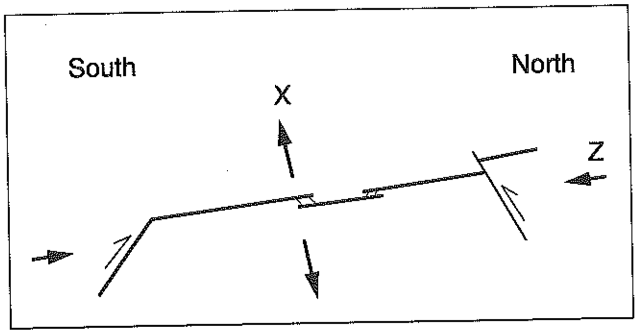

Figure 11. Schematic diagram showing the main structural elements associated with the No. 1 vein and the interpreted external bulk strain axes.

Development and propagation of the No. 1 vein

As outlined in the preceeding paragraphs, the No. 1 vein clearly did not result from the propagation of a single continuous extensional fracture. It rather formed by the coalescence of several first-order extensional veins linked by second-order ones to produce shallow-dip segments, which are in turn linked by moderate-dip fault-fill veins.

In a number of relay zones, the north and south terminations of overlapping first-order veins have a sigmoidal shape (Fig. 3C, 4C). Such a pattern is identical to that predicted for the interaction between two extensional cracks propagating toward each other, as a result of stress refraction at crack tips (Pollard et al., 1982). In three dimensions, one can consider that the axis of the relay zone between the two propagating cracks will be perpendicular to their local propagation directions. By analogy, the intersections between first- and second-order veins in relay zones should also be at high angles to the local propagation direction. Thus, axes of relay zones, intersection between first- and second-order veins, as well as axes of rock bridges could all tentatively be used to approximate the propagation direction of individual first-order extensional veins. The orientation of these structural elements (Fig. 5B) indicates propagation of first-order extensional veins along northeast and north directions. These very preliminary results suggest that one can use such structural features to understand the development of large extensional veins as at Donalda.

DISCUSSION

The overall geometry of the Donalda deposit, combining moderately dipping reverse shear zones and shallowly dipping extensional veins is similar to that of other shear-zone-related quartz-carbonate vein gold deposits. The interpreted north-south compressional regime at Donalda is also common to many other deposits of this type in southern Abitibi, where it is generally ascribed to a D2 increment of crustal shortening (Robert, 1990). This suggests that, despite the unique extensive development of extensional structures, the Donalda belongs to shear-zone-related quartz-carbonate vein type of gold deposits. This similarity is further supported by a fluid inclusion study (Chi et al., 1992), which shows that fluids at Donalda are typical of those found in this class of gold deposit: H_2O-CO_2, low salinity fluids, CO_2-rich fluids, and aqueous saline inclusions.

Like at many other shear-zone-related gold deposits, the Donalda vein is spatially associated with a major fault zone, the Horne Creek fault. However, field relations indicate that there are no temporal nor genetic relations between the two types of structures. There is a major kilometric stratigraphic offset along this fault (Fig. 1; Riverin et al., 1990), but the offset of the Donalda vein by the fault is only in the order of a few tens of metres at most (Fig. 2). This indicates that most of the movement along the Horne Creek fault pre-dates the vein and that there was minor post-vein reactivation of the fault, after intrusion of the diabase dyke. Furthermore, the nearly complete absence of veins and alteration within the Horne Creek fault at Donalda indicates that it did not serve as a major conduit for migration of hydrothermal fluids. As noted above, the Donalda deposit occurs in the vicinity of the Horne and Quemont auriferous VMS deposits (Fig. 1). The temporal relationships between the Donalda vein and the Horne Creek fault indicate that the vein is decidedly post-volcanic and has no genetic relation to the VMS deposits. However, it cannot be excluded that some of the Donalda gold was derived from these auriferous VMS deposits.

Finally, it is worth noting the geometric similarities between the Donalda deposit and those of Norseman, Western Australia (O'Driscoll, 1953). The main mineralized veins at Norseman (Mararoa, Crown and Royal) dip 45° and, as at Donalda, they consist of en échelon moderate-dip veins, hosted in reverse shear zones, linked by shallow-dip extensional veins (McKinstry, 1942). The difference at Norseman is that the shallow-dip extensional segments are less extensive than the moderate-dip shear-zone-hosted segments and define a "shear-link" geometry, in which extensional veins link more continuous fault-fill veins (McKinstry, 1942). An opposite situation occurs at Donalda, where the shear-zone-hosted veins are the links between extensional veins.

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