

UNIVERSITÉ DU QUÉBEC À MONTRÉAL

TWO STYLES OF STRUCTURAL HYDROTHERMALISM IN ARCHEAN SHEAR
ZONES, THE CASE OF THE PORCUPINE-DESTOR SHEAR ZONE, ABITIBI,
CANADA

MÉMOIRE
PRÉSENTÉ
COMME EXIGENCE PARTIELLE
DE LA MAÎTRISE EN SCIENCES DE LA TERRE

PAR
RAPHAËL DOUTRE

SEPTEMBRE 2010

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UNIVERSITÉ DU QUÉBEC À MONTRÉAL

DEUX STYLES D'HYDROTHERMALISME STRUCTURAL DANS LES ZONES DE
CISAILLEMENT ARCHÉENNES, LE CAS DE LA FAILLE PORCUPINE-DESTOR,
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AVANT-PROPOS

Ce mémoire est rédigé sous la forme d'un article qui sera soumis à la revue *Journal of Structural Geology* (Elsevier). Sa présentation est donc différente de celle des mémoires habituellement présentés à l'UQAM. Notamment, la langue de rédaction est l'anglais et les figures et tableaux sont situés à la fin de l'article. Moi-même et Michel Jébrak sommes auteurs de cet article. Ce format de mémoire a été choisi car il donne l'opportunité de transmettre de nouvelles connaissances à la communauté scientifique à l'échelle internationale.

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RÉSUMÉ

Les veines sont parmi les structures les plus communes et les mieux développées le long des zones de cisaillement. Dans la ceinture de roches vertes de l'Abitibi (Canada), des systèmes de veines bien exposés le long de la zone de cisaillement Porcupine-Destor permettent d'étudier les conditions de contraintes dans lesquelles les veines se sont mises en place. Les systèmes de veines ont pu être caractérisés en examinant la texture, la géométrie, la distribution, l'espacement, l'épaisseur, et la longueur des veines, ce qui a permis de déterminer la surpression de fluide. La surpression de fluide moyenne pour l'un des systèmes de veines est estimée à 42 MPa, ce qui correspond à une profondeur de mise en place de 2.7 km. Ces estimations ont permis de modéliser l'état des contraintes lors de la phase de compression régionale. Les contrastes de compétence génèrent de fortes perturbations des contraintes le long de la zone de cisaillement. Dans la séquence de roches, la zone de cisaillement Porcupine-Destor agit comme une unité lithologique de faible compétence et génère une zone de faibles contraintes très favorable à la formation de veines. Vingt-cinq kilomètres plus à l'est, les veines se sont mises en place dans un contexte de faille-valve à fonctionnement cyclique; ceci indique que les veines résultent de la perturbation temporaire de l'état de contraintes lors de ruptures sismiques. Ces deux mécanismes de perturbation de la contrainte sont favorables à la formation de veines le long des zones de cisaillement.

MOTS CLÉS : Veines, Zones de cisaillement, Contraintes, Contraste de compétence, Abitibi

INTRODUCTION GÉNÉRALE

Les systèmes de veines aurifères, formant les gisements d'or filoniens orogéniques, sont très bien développées le long des zones de cisaillement majeures (Robert and Poulsen, 2001; Groves et al., 2003). Cependant, des systèmes de veines stériles sont souvent observés. Pourquoi un système de veines est-il aurifère ou stérile? À l'intérieur de la croûte, proche de la transition fragile-ductile, là où la plupart des gisements d'or filoniens orogéniques se forment, la perméabilité structurale est essentielle pour concentrer les fluides aurifères (Sibson, 1996, 2004; Cox, 2005; Phillips and Powell, 2009). Ces fluides sont susceptibles d'avoir migré sur de longues distances à travers d'importants volumes de roches, ce qui a pu permettre l'enrichissement en métaux (Cox, 2005). Lorsque des zones de cisaillement actives sont connectées au réservoir de fluides, le comportement de faille-valve permet le pompage des fluides (Oliver, 2001; Sibson et al., 1988). Ce mécanisme de concentration des fluides est essentiel pour la formation des gisements d'or filonien (Sibson, 2004). Les zones où les structures sont fortement connectées et densément développées sont des sites de perméabilité maximale où les fluides vont se concentrer pour former des gisements d'or (Cox, 2005; Cox et al., 2001; Kenworthy and Hagemann, 2007).

La formation des veines dépend essentiellement de l'interaction entre la pression de fluide et la contrainte tectonique dans un régime cassant (Cox, 2005). Dans une séquence de roches subissant une déformation, les veines sont susceptibles de se former dans les zones où la contrainte est hétérogène. Ces zones se développent le long de zones de failles ou de cisaillements actives, dans les plis, et dans les secteurs à forts contrastes de compétence. D'une part, les zones de failles ou cisaillements actives permettent une modification de la contrainte par l'intermédiaire du comportement de faille-valve. D'autre part, les roches très déformées des zones de failles et cisaillements représentent de forts contrastes de compétence qui vont modifier l'état de contrainte local dans la séquence de roches (Gudmundsson et al., 2009). Ces deux pôles de mécanismes de perturbation de la contrainte sont favorables pour former des veines le long d'une zone de cisaillement.

Cet article traite de l'analyse structurale de deux systèmes de veines développés le long d'une zone de cisaillement majeure archéenne. Une étude structurale détaillée a été

menée sur des surfaces de décapages. Les données de forages et la carte aéromagnétique ont permis de réaliser des cartes géologiques. Les systèmes de veines sont exposés dans deux secteurs distants de 25 km. Tout d'abord, la géologie du secteur MacCormack est présentée. Dans ce secteur, les veines sont stériles et sont développées dans une enveloppe d'environ 500x1000 m qui recoupe la zone de cisaillement majeure. Ensuite, la géologie du secteur Rambull est dévoilée. Ce secteur est caractérisé par des veines aurifères qui sont contemporaines à des cisaillements subsidiaires. Puis, ces deux contextes sont comparés et les implications sur l'état des contraintes sont examinées. Dans le secteur MacCormack, une modélisation numérique de l'état des contraintes suggère que les contrastes de compétences sont susceptibles de générer des systèmes de veines stériles le long des zones de cisaillement majeures. Ceci suggère que le comportement de faille-valve est critique pour la formation de filons aurifères orogéniques. Ce modèle a des implications sur la genèse des gisements d'or filoniens et a donc un intérêt pour l'exploration minérale.

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**TWO STYLES OF STRUCTURAL HYDROTHERMALISM IN ARCHEAN SHEAR
ZONES, THE CASE OF THE PORCUPINE-DESTOR SHEAR ZONE, ABITIBI,
CANADA**

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Abstract

Veins are one of the most common structural features along shear zones. In the Abitibi greenstone belt (Canada), well-exposed vein systems along the Porcupine-Destor shear zone provide insight into the role of stress state at the time of vein formation. The vein systems were characterised by analysing the texture, geometry, distribution, spacing, thickness and length of veins and the magnitude of the driving stress was determined. The average driving stress for one of the vein systems is 42 MPa, and the corresponding depth of vein formation is estimated at 2.7 km. These values allowed performing numerical modeling of the stress during regional shortening. Competency contrasts generate strong stress perturbations along the major shear zone. The Porcupine-Destor shear zone acts as an incompetent rock unit within the intact rock sequence, which leads to strong stress lowering in the shear zone. This low stress was highly favourable for vein formation. At 25 km away along the shear zone, veins formed during the fault-valve cycle indicating transient stress perturbation during earthquake rupturing along the shear zones. The model suggests that these two end-member mechanisms of stress perturbation may lead to vein formation along a shear zone.

Keywords: Veins, Shear zones, Stress, Competency contrasts, Abitibi

1. Introduction

Gold-bearing veins forming orogenic lode gold deposits are extensively developed along major Archean shear zones (Robert and Poulsen, 2001; Groves et al., 2003). However barren vein systems are widespread and it remains unclear why a vein system is mineralised or not. At depth in the crust, near the brittle-ductile transition where most of the orogenic lode gold deposits form, structural permeability plays a critical role in focusing gold-bearing fluids (Sibson, 1996, 2004; Cox, 2005; Phillips and Powell, 2009). Such fluids are likely to have circulated on long distances through large volume of rocks, allowing metal enrichment (Cox, 2005). Networks of active shear zones, where connected to a fluid reservoir, promote fluid drainage through fault-valving behaviour (Oliver, 2001; Sibson et al., 1988). Such mechanism is essential for fluid concentration and formation of gold-bearing vein systems (Sibson, 2004). Areas where structures have high connectivity and density represent sites of greatest permeability where fluids migrate to form gold deposits (Cox, 2005; Cox et al., 2001; Kenworthy and Hagemann, 2007).

Vein formation largely results from interplay between fluid pressure and tectonic stress in brittle deformation conditions (Cox, 2005). In a deforming rock sequence, veins are expected to form in zones of heterogeneous stress which largely develop along active faults, shear zones, and folds, and in areas of competency contrasts. On one hand, active faults and shear zones promote modification of the stress state through fault-valving behaviour. On the other hand, strained rocks in fault and shear zones may represent high competency contrasts that modify the local stress state in the rock sequence (Gudmundsson et al., 2010). These two end-member mechanisms for stress perturbation may both lead to vein formation along a shear zone.

This paper reports on structural analysis of two distinct vein systems present along a major Archean shear zone. Stripped outcrop surfaces allowed detailed study on the field and boreholes and aeromagnetic map were used to trace solid geological maps. Vein systems occur in two areas separated by 25 km. First, we describe the MacCormack area, where veins are barren and occur within a ~500x1000 m envelope which cuts the major shear zone. Second, we analyse the Rambull area where gold-bearing veins emplacement is synchronous with shearing and faulting along low order shear zones. These two case studies are compared

and stress conditions for vein formation are examined. Numerical modeling of the stress in the MacCormack area suggests that competency contrast is important for formation of barren vein systems along major shear zones. This suggests fault-valve behaviour is critical for the formation of orogenic lode gold deposits. This model has direct implications for distinguishing barren from mineralised vein systems, and is therefore of interest to genesis of orogenic lode gold deposits and mineral exploration.

2. Regional geology

The Abitibi belt is the largest greenstone belt in the world, extending 400 km E-W by 250 km N-S. This region is one of the most prolific gold and base metal producer in the world and hosts several major mining camps. It is located in the southeastern portion of the Superior Province, Canada. This belt is similar to many other greenstone belts from the Superior Province and the Yilgarn craton of Western Australia (Robert et al., 2005).

The Abitibi belt is bordered by Archean rocks from the Pontiac Subprovince to the south and from the Opatica belt to the north. The belt is truncated by two major Proterozoic structures on its western and eastern limits, the former being the Kapuskasing structure, a major thrust, and the later the Grenville orogenic front (Figure 1a).

2.1. Abitibi belt stratigraphy and deformation

Two major models exist for the formation of the Abitibi greenstone belt. The first model suggests the belt is composed of allochthonous terranes that accreted during collisional tectonics, comparably to modern orogenic belts (Dimroth et al., 1983; Kerrich and Feng, 1992; Mueller et al., 1996). The second model proposes that the belt developed as a large autochthonous terrane. It suggests the stratigraphy throughout the belt is upward-facing, upward younging, and is folded on a regional scale (Peschler et al., 2006; Thurston et al., 2008).

The belt is composed of metavolcanic, granitic, and metasedimentary rocks (Figure 1a). The stratigraphy is largely represented by volcanic rocks, which deposited continuously over a period of ca. 55 Ma, between 2750 and 2695 Ma (Mueller et al., 1996; Ayer et al., 2002; Goutier and Melançon, 2007; Thurston et al., 2008). The period of volcanism was followed by siliclastic sedimentation during about 20 Ma, which emplaced in successor basins unconformably overlying the volcanic rocks. Plutonism in the belt spans the same age range as volcanism and sedimentation, but continued until about 2640 Ma.

Regional metamorphic grade affecting the rocks is subgreenschist to greenschist, and took place at ca. 2660 Ma (Powell et al., 1995). Amphibolite metamorphic grade is also locally present as contact aureoles around plutons. Maximum burial during peak metamorphism corresponded to about 10 km depth (~200 MPa; Powell et al., 1995).

The Abitibi belt has undergone a regional N-S shortening that began at ca. 2700 Ma and lasted at ca. 2660-2650 Ma (Peschler et al., 2006). The principal resulting structures are regional-scale E-W trending folds and shear zones. Folds have half-wavelength of 10-40 km and affect the upper and middle crust (Benn and Peschler, 2005; Peschler et al., 2006). Folding is largely responsible for the actual geometry of the belt. Batholith diapirism, associated tilting of strata, and synclinal keels suggest that vertical tectonism played a major role in the regional deformation (Becker and Benn, 2003; Peschler et al., 2006). The deformation of the whole belt could also have been the result of synchronous vertical and horizontal tectonism (Lin and Beakhouse, 2008).

Although the Abitibi greenstone belt contains numerous major shear zones (Figure 1a), two of them have particularly large dimensions with more than 350 km in length; they are the Porcupine-Destor and Kirkland-Cadillac shear zones. These two shear zones are by far the most studied in the Abitibi greenstone belt, because they have been the loci of major gold deposits (Robert et al., 2005).

2.2. Shear zones

Interpretations of seismic and gravity data show that the Kirkland-Cadillac shear zone is a crustal-scale feature (Benn, 2006). Analyses on other major shear zones are

divergent and either suggest these structures are limited to the upper crust or they extend into the deep crust (Jackson and Sutcliffe, 1990; Benn, 2006; Bateman and Bierlein, 2007). There is no marker indicating offset on major shear zones; however numerous studies suggest offsets are not noticeable on a regional scale (Powell et al., 1995; Benn and Peschler, 2005; Peschler et al., 2006; Snyder et al., 2008; Thurston et al., 2008).

The Porcupine-Destor and Kirkland-Cadillac shear zones display numerous second- and third-order shear zones. These lower order structures are hundreds to thousands of meters long and are the loci for orogenic gold deposits, whereas deposits rarely occur within the main structures (Robert et al., 1995; Bateman and Bierlein, 2007). The shear zones record ductile to brittle-ductile deformation. A few of these major structures, such as the Main Break at Kirkland Lake, which hosts major gold deposits, represent brittle faults that formed at shallower depth (Dubé and Gosselin, 2005).

Major shear zones movement depends on their orientation. East-west trending shear zones record vertical movement, whereas northwest- and northeast-trending shear zones indicate dextral and sinistral movements, respectively (Daigneault et al., 2004, Fig. 2). Such various movements can occur along a single shear zone (Wilkinson et al., 1999). The regional structures and associated movements are very similar to those described in the Yilgarn craton of Western Australia (Chen et al., 2004). Final stage of movement is marked by a progressive transition from reverse to dextral transcurrent regime on some east-west trending shear zones (Robert, 1989; Robert et al., 2005). The few available studies dealing with movements along the Porcupine-Destor shear zone indicate it experienced vertical movement in some areas and strike-slip movement in others (Mueller et al., 1996; Daigneault et al., 2002; Benn et al., 2001; Benn and Peschler, 2005).

Regional shear zones represent zones where deformation and commonly metamorphism are more intense than within the background. In the most strongly foliated rocks, the primary mineralogy is entirely replaced by alteration minerals indicating voluminous fluid fluxes during regional metamorphism (Wilkinson et al., 1999; Benn and Peschler, 2005).

Previous models have interpreted the Porcupine-Destor and Kirkland-Cadillac shear zones to be basin-bounding fault zones that were reactivated during regional shortening or

major terrane sutures formed during orogenic collision (Dimroth et al., 1983; Kerrich and Feng, 1992; Mueller et al., 1996). In accordance with an autochthonous development of the belt, more recent models suggest the shear zones formed on regional fold limbs during shortening of the belt (Peschler et al., 2006; Benn and Peschler, 2005).

3. Methodology

3.1. Vein measurements

Veins were systematically measured along lines parallel to the vein opening direction, when obvious and marked by quartz fibres, or perpendicular to the veins in other cases. This sampling technique is used to typify the geometry of a vein array (Gillespie et al., 1999). The thickness (W), length (L) and spacing (S) of veins were measured (Figure 2a). Where veins were only partly exposed, the largest veins were likely to be undersampled, which causes a censoring effect in the analysis (Bonnet et al., 2001). Smaller veins which were not measurable with conventional field methods were also undersampled, which causes a truncation effect.

The coefficient of variation of vein spacing, C_v , is a measure of the clustering of veins along a line and is defined as:

$$C_v = SD(S)/m \quad (1)$$

where $SD(S)$ is the standard deviation of vein spacing and m is the mean vein spacing. When $C_v = 1$, veins are randomly spaced; $C_v > 1$ indicates clustering or irregular spacing of veins and $C_v < 1$ indicates anti-clustering or regular spacing of veins (Gillespie et al., 1999).

If veins are anti-clustered, the vein density is approximated homogeneous along a single line sample. Thus, the vein density in a line sample is:

$$d = N/l \quad (2)$$

where N is the number of veins and l is the length of the sampling line, with unit in meter.

As extension veins represent infill of open space due to extension during deformation, the total vein thickness (w) measured perpendicularly to veins along a line provides an estimate of the bulk extensional strain in a parallel vein array such as:

$$e = (w/l)100 \quad (3)$$

where e is the percentage of bulk extensional strain in the rock along the sampling line.

Vein geometric features (thickness, length, spacing) can be analysed in terms of their cumulative frequency distribution. Vein thicknesses (W) are plotted versus their cumulative frequencies ($N(\geq W)$) on diagrams with log-log axes. On such diagrams, a straight line indicates a power law distribution of the form (Loriga, 1999):

$$N(\geq W) = cW^{-D_w} \quad (4)$$

where c is a constant and D_w is the scaling factor or fractal dimension. The power law exponent $-D_w$ is the slope of the line. This value varies according to the thickness distribution of the veins in the population and is not affected by the number of measures. Higher values of D_w , i.e. a steeper slope on the plot, mean that there are relatively more thin veins than thick veins (Loriga, 1999; Gillespie et al., 1999). Such analysis can be done for vein length or spacing. Censoring and truncation effects are likely to perturb the power law distribution on the plot for higher and lower values, respectively, but do not modify the slope of the line.

The vein aspect ratio (L/W) is defined as the ratio between vein length and vein maximum thickness. It may be plotted on a diagram with $\log(L)$ vs. $\log(W)$ axis. On such plots, data lying on a straight line may be described by a power law relationship of the form:

$$L = pW^a \quad (5)$$

where p is a constant and a is the power law exponent. The value of p represents the average vein aspect ratio for the dataset; the value of a determines the change in aspect ratio with scale (Johnston and McCaffrey, 1996). For $a = 1$, vein aspect ratio is self-similar, i.e. it does not change with scale. For $a \neq 1$, aspect ratio is self-affine, it varies with scale. Ideally, measured veins must meet the following criteria (Gudmundsson, 1999): (1) veins are mode I fractures with no shear displacement; (2) veins are non-restricted, i.e. they do not end by

intersecting other veins or rock discontinuities; (3) vein length is defined as the linear distance from the ends of a continuous mineral-filled fracture.

Measuring the aspect ratio of veins (Figure 2) allows estimating the driving stress for isolated and echelon veins.

3.2. Driving stress calculation

For a pure extension vein, the driving stress (ΔP) is the difference between the fluid pressure (P_f) within the fracture and the remote normal stress (σ_3). Any positive driving stress ($P_f > \sigma_3$) produces some dilation. For an isolated vein (Figure 2a), the driving stress is given by:

$$\Delta P = (W\mu) / (L(1 - \nu)) \quad (6)$$

where μ is the shear modulus of the rock and ν is its Poisson's ratio (Pollard and Segall, 1987). Note that for a specific rock ΔP increases linearly with vein aspect ratio.

On the other hand, the driving stress for echelon veins (Figure 2b) is given by:

$$\Delta P = (W\mu) / (kND(1 - \nu)) \quad (7)$$

where k is the center spacing measured parallel between two veins and ND is the normalized dilation (Nicholson and Pollard, 1985). The spacing between two veins is s and the total length of the echelon vein array is L' (Figure 2b). The ratios L/k and s/k are used to determine graphically the value of ND on Fig. 6 from Nicholson and Pollard (1985). The ratio L/k reflects the overlap ratio between two veins and for $L/k > 1.0$ veins overlap.

Veins behave as isolated veins if $L/k < 0.5$ or $s/k > 1.0$, and in this case Eq. (6) is applicable. Veins with $s/k < 0.1$ and $L/k > 1.5$ have a thickness approaching the thickness of an isolated vein of length L' . In other words, the aspect ratio W/L' is smaller but close to the aspect ratio of an isolated vein, and ΔP value calculated using W/L' will approach the ΔP value for an isolated vein.

Gudmundsson (1983) calculates the depth of formation of dykes by utilizing the driving stress determined with dyke aspect ratio. The depth is given by:

$$z = \Delta P / ((\rho_r - \rho_m)g) \quad (8)$$

where ρ_r is the fractured rock density, ρ_m is the magma density and g is the acceleration due to gravity. This equation has been used to estimate the depth of formation for hydrothermal veins (Vermilye and Scholz, 1995).

3.3. Paleostress modeling

The UDEC (Universal Distinct Element Code) software is useful for modelling the stress state in a rock sequence where rocks show predominantly brittle behaviour (Holyland and Ojala, 1997; Oliver et al., 2001). The model is in two dimensions and is based on a solid geological map. It is divided into blocks of different rheologies which represent the lithological units. Limits between blocks represent contacts. Parameters are assigned both to blocks and contacts. Stress is applied to the boundaries of the model to simulate a regional compression, which results in modification of the stress state into the rock sequence. The aim is to test if rock competency contrasts and/or contacts have an influence on the distribution of the stress in the deforming rock sequence. The reader is referred to Oliver et al. (2001 and references therein) for further explanation on the principles of UDEC and its application.

4. MacCormack area

4.1. Geology

The stratigraphic sequence is an E-W trending overturned volcanic pile, steeply dipping to the north (Figure 3a). The rocks are dated at 2718 to 2716 Ma and are equivalent to rocks from the Kidd-Munro group in Ontario (Pilote et al., 2008). The Porcupine-Destor shear zone developed in ultramafic and mafic volcanics parallel to the bedding. The shear zone thickness is up to 200 m. It is composed of a locally anastomosing core zone and do not exhibit subsidiary structures. Foliation fabrics and veins are widespread. Oblique lineation and kinematic indicators suggest dextral-reverse movement (Figure 4a and 7b).

Syntectonic calc-alkaline to alkaline porphyric granitoid intrusions are present along the shear zone (Figure 1b and 3). This type of intrusion is common along the Porcupine-Destor shear zone which controlled their emplacement on a regional scale between 2682 and 2672 Ma (Robert, 2001; Legault et al., 2006). At MacCormack, the main intrusion occurs in a fold hinge (Figure 3a).

The country rocks (this term designates the rocks in the immediate vicinity of the shear zone on Figure 3a) display preserved primary mineralogy and are not to weakly foliated (Figure 7c). Previous studies proposed a greenschist grade metamorphism for the area, although sub-greenschist metamorphism occurs a few km further north (Daigneault et al., 2004, Fig. 2d). Rocks from the shear zone are strongly foliated and the primary mineralogy is entirely replaced by chlorite-iron carbonate and fuchsite-iron carbonate assemblages (Figure 7a, b). Rock geochemistry suggests the former assemblage protolith was a basalt and the later was an ultramafic rock. Hydrothermal alterations also include gold-enriched more local albite, sericite and pyrite replacement zones which mainly emplaced during ductile deformation (Renou, 2009).

The regional foliation (S1) is E-W trending and steeply dipping to the north (Figure 4a). It is subparallel to the stratigraphic sequence, except to the north-west where it is at high angle (Figure 3a).

Within the shear zone, stratigraphic contacts are obliterated and transposed parallel to the S1 foliation (Figure 3b). Stretching lineation (L1) systematically plunges 30-40° W along the shear zone and ~70° W in the country rock (Figure 4a). A S2 foliation is developed only locally within the shear zone. This foliation is weakly penetrative. It is NE-trending, steeply dipping to the north and axial planar to F2 folds (Figure 3b and 4a). These folds are mostly Z-shaped. Where present, the S2 foliation systematically folds, and thus postdates the intrusions emplacement. A few km away along the shear zone, the S2 foliation is rare.

The NE trending S2 foliation, associated Z-shaped folds of S1 and the shallow plunge of the L1 stretching lineation within the shear zone suggest the Porcupine-Destor shear zone is an oblique dextral transpression zone in the MacCormack area, such as described 30 km further west by Mueller et al. (1996). The shear zone developed during

regional subhorizontal N-S shortening and the D2 deformation phase is confined to this zone and its vicinity.

4.2. Vein system

For comparison, the veins emplaced within the shear zone are treated separately from those emplaced into the country rocks. Veins have three main orientations: E-W, NE-SW and NW-SE (Figure 4b). Dips are moderate to vertical, but subhorizontal veins locally occur in the country rock. Veins have very similar orientations in the shear zone and in the country rock, which suggests they emplaced during the same deformation event. The veins are pure extension veins, with the opening vector normal to the vein walls (Figure 7c). Veins are filled with quartz within the country rock (Figure 10a). A few veins also display iron carbonate and calcite. Within the shear zone, veins are filled with quartz and iron carbonate. Iron carbonate crystals are frequently idiomorphic and are a few mm to several tens of cm large within the largest veins. These crystals are attached to the vein walls or isolated within the xenomorphic quartz, showing they crystallized first. Veins hosted by the intrusions are filled with quartz, and locally with iron carbonate.

Within the shear zone, veins cut and postdate the rock alteration and the S1 foliation (Figure 3b). They locally contain fragments of their altered hostrock. Veins have mutual crosscutting relationships and locally form meshes. Some veins are boudinaged. Folded veins are frequent within the shear zone and absent outside (Figure 3b and 7c, d). E-W trending veins are subparallel to the S1 foliation and NE-SW trending veins are subparallel to the S2 foliation (compare Figure 4a and 4b). Locally, NE-SW trending veins fill the S2 foliation plane and branch to veins folded by S2.

The above description suggests all veins formed through the D2 deformation phase during NW-SE shortening. As veins are pure extension veins, their formation implies a switching in the orientation of the minimum compressive stress.

Most veins are arranged in parallel arrays where veins have a single orientation and are unconnected (Figure 7d). Vein arrays are a few to ~25 m large. The largest arrays trend E-W and are subparallel to the S1 foliation. Veins systematically show echelon or segmented

geometries and isolated veins are almost absent. Except for veins that exploit the foliation planes, all the veins are newly formed. Rocks locally display hydraulic breccia textures with jigsaw puzzle patterns. The two later observations suggest vein formation and propagation was the result of high fluid pressure relative to stress, as also indicated by the occurrence of broken bridges and euhedral crystals in the veins.

Veins show a strong lithological control within the shear zone: they are developed in strong fuchsite zones and intrusions and are absent in softer chlorite zones. The same relations occur further west along the shear zone (Legault et al, 2006). Veins are unrestricted, i.e. non stopped by a discontinuity, except in some cases where they are restricted by the boundaries of chlorite zones (Figure 3b). Within the less deformed country rock, veins are developed in massive rhyolite and basalt and crosscut stratigraphic contacts mostly without showing perturbations. In all the area, vein arrays may have emplaced and freely develop mostly without interacting with rock unit boundaries.

Several observations within the shear zone are relevant to estimate the origin of vein filling material. As previously described, veins postdate the rock alteration. Veins never show alteration halos in their hostrock. Some veins locally contain much more carbonate where their immediate hostrock shows greater carbonation. Moreover, veins emplaced in the core of small intrusions embedded within the altered sheared rock contain only quartz, whereas a few m away veins hosted by fuchsite zones contain quartz and iron carbonate. All these observations, associated with the fact that veins are rarely interconnected, strongly suggest that vein forming fluid came from local in-situ remobilization postdating the rock alteration.

4.2.1. Vein statistics

The thickness, length and spacing of veins were systematically measured in the shear zone and in the country rock. The statistics are listed in Table 1. Within the shear zone, vein maximum thickness is 350 cm for veins parallel to the S1 foliation and 19.9 cm for the other veins. Within the country rocks, vein maximum thickness is 4.7 cm within the rhyolite and 1.2 cm within the basalt. Average bulk extensional strain is about five times higher within the shear zone than outside. Veins are much thicker within the shear zone, especially veins

parallel to S1. The S1 foliation plane represents a strong anisotropy which may have favoured greater dilation during vein aperture.

Veins are anti-clustered or regularly spaced in the MacCormack area, with average C_v values of $0.76 (\pm 0.15)$ in the shear zone and $0.83 (\pm 0.21)$ in the country rock. Average spacing, density and clustering of veins are about the same in the shear zone and in the country rock, showing spacing does not vary according to rock type (Table 1).

Cumulative frequency of vein spacing is plotted in Figure 8a. Data from the shear zone represent the spacing for two combined line samples measured on a single vein array; data from outside the shear zone represent the spacing for four combined line samples measured on one outcrop on parallel vein arrays. Combining of the line samples did not modify the general shape of the curves. Spacing shows approximately log-normal distributions which are identical within and outside the shear zone, as represented by parallel curves on Figure 8a which are not superposed because the number of measures is different for the two datasets. The only difference is the greater steepening of the curve at greater spacing for veins outside the shear zone; this may be caused by the presence of the same large spacing values in several proximal line samples or higher censoring effect (Gillespie et al., 1999; Bonnet et al., 2001).

Cumulative frequency of vein thickness is plotted in Figure 8b for veins from the shear zone and the country rock rhyolite. Vein thicknesses show power law distributions with $D_w = 0.40$ within the shear zone and $D_w = 0.99$ in the country rock. This high difference in D_w means that veins are much thicker within the shear zone than outside, which is consistent with field measurements (Table 1).

Cumulative frequency of vein length for the same veins is plotted in Figure 8c. Vein lengths show power law distributions with $D_L = 0.42$ within the shear zone and $D_L = 0.86$ in the country rock. This suggests that veins are longer within the shear zone than outside. For $L > 85$ cm veins within the shear zone show a steepening with $D_L = 1.59$; this is probably due to undersampling of longer veins (censoring effect; Bonnet et al., 2001).

The length and maximum thickness of veins were measured for 237 veins in the MacCormack area. Measures include 194 veins from the fuchsite zones within the shear zone and 43 veins from the country rock rhyolite. Veins from the shear zone give the relationship

$L = 49W^{0.82}$ and veins from the rhyolite give $L = 309W^{1.01}$ (Figure 8d). Vein average aspect ratio (L/W) is 49 within the shear zone and 309 in the rhyolite. Veins are six times more dilated within the shear zone than in the country rock rhyolite. This result is consistent with the calculated bulk extensional strain and the cumulative frequency plot of vein thickness (Table 1; Figure 8b). The power law exponent value $a = 1.01$ for the rhyolite suggests that veins grew by thickening as much as by lengthening. On the other hand, the value of $a = 0.82$ suggests that veins grew more by thickening than lengthening within the shear zone (Johnston and McCaffrey, 1996).

Statistics of veins clearly indicate that vein arrangement is approximately identical within and outside the shear zone, but vein shape is different with thicker veins within the shear zone.

5. Rambull area

5.1. General geology

The rock sequence is an E-W trending overturned volcanic pile, steeply dipping to the north, such as at MacCormack. However, rock types and deformation are very different at Rambull (Figure 5a). This study area is located 3 km north from the Porcupine-Destor shear zone (Figure 1b). The rocks are dated at 2719-2718 Ma and belong to the Deguisier Formation (Pilote, pers. comm., 2009). Rocks include metamorphosed pillowed and massive basalt, gabbro and granodiorite. The granodiorite is locally cut by synvolcanic gabbro intrusions which have the same composition than basalts, indicating this pluton is synvolcanic and predate deformation. Systematic chlorite replacement in all rocks indicates they undergone greenschist grade metamorphism. All the rocks are affected by the regional foliation (S1) which is largely defined by micaceous minerals. The foliation trends E-W and dip steeply to the north; it is subparallel to the stratigraphy (Figure 5a). The stretching lineation is down-dip. Pillowed basalts from the background show an aspect ratio of 1:2 to 1:5 in plan view. A major throughgoing shear zone, the South Rambull shear zone, developed along the lithological contact separating two distinct basalt units. The observed shear zone

thickness is 30 m and the total thickness is unknown. The systematic occurrence of steps on the foliation surface in all shear zones indicates their ductile-brittle nature.

The basalt and the granodiorite exhibit two very different deformation styles. As a consequence, the area has been subdivided in two distinct parts which are (1) the South Rambull area, represented by the basalts to the south of the granodiorite, and (2) the North Rambull area, represented by the granodiorite (Figure 5a).

5.2. Shear zones and veins at South Rambull

At South Rambull, basalts host synvolcanic gabbro sills (Figure 5c and 7h). Foliation is more penetrative within the basalt than in the gabbro, suggesting the later was more competent. Shear zones are subparallel to the stratigraphy and are developed within the basalt at gabbro layers boundaries. Basalt pillows have an aspect ratio of about 1:40 at shear zone margins and are obliterated within the shear zones. No shear zones occur at more than ~30 m away from the South Rambull shear zone. The shear zones are composed of sericite and chlorite on their margins. Stretching lineations indicate vertical movement (Figure 6a). Shear sense is unknown. The shear zones do not exhibit subsidiary structures, but only rare anastomosing through the gabbro layers.

Most veins are hosted by gabbro sills (Figure 5c and 7h). Veins have various orientations and steep dips. Some veins are also subhorizontal; they trend E-W and gently dip to the south (Figure 6b). Veins are pure extension and extensional-shear veins, with the opening vector normal and oblique to the vein walls, respectively (Figure 7g, h and 10b). Some shear veins locally occur. With the occasional exception, N-S trending and subhorizontal veins are pure extension veins and other veins are extensional-shear veins (Figure 6b). The later veins display a conjugate set where NE-SW and NW-SE trending veins have sinistral and dextral opening, respectively; they also show crack-seal textures (Figure 7g and 10b). Veins are filled with quartz, chlorite, ankerite and locally sericite. A few veins contain gold. Some veins are surrounded by an alteration halo, indicating the filling fluid reacted with host rock (Figure 7g).

Competent gabbro sills had a strong control on vein formation. Veins are confined to the sills and stop when approaching their boundaries (Figure 7h). In some cases, veins crosscut the contacts and propagate in the basalt on a short distance. In thick gabbro sills most veins are short relative to the size of the layer and are unrestricted. The large majority of veins are restricted by gabbro layers boundaries, and stratabound vein arrays are frequent. Commonly, veins are sinuous, deviated and show branching geometries. Subvertical veins locally show horizontal diversion. Veins are thicker when oriented toward the north and are frequently folded.

A significant observation is that the shear zones do not contain any vein, indicating they did not play a role in vein formation mechanism. They show mutual crosscutting relationships with rare extension veins extending out of the gabbro, indicating shear zones and veins are contemporaneous. Moreover veins are also developed in areas where shear zones are absent. Thus, at South Rambull vein emplacement was largely controlled by rock competency and not by shearing or faulting.

Veins are anti-clustered in the South Rambull area, with an average C_v of 0.66 (± 0.1), which is a typical behaviour in stratabound arrays (Gillespie et al., 1999).

Cumulative frequency of vein spacing, thickness and length are plotted in Figure 9. Spacing shows approximately log-normal distributions for stratabound vein arrays (Figure 9a); unrestricted vein arrays gave similar plots. Unrestricted vein arrays show power law thickness distributions whereas stratabound arrays display approximately log-normal distributions (Figure 9b). Vein length suggests a power law distribution for unrestricted vein arrays. For stratabound arrays, length distributions show that most veins have a characteristic length, which is controlled by gabbro units thickness (Figure 9c).

As vein arrays are stratabound, thickness, length and spacing of veins may be highly influenced by the thickness of the host rock layer (Wu and Pollard, 1995; Ji et al., 1998). The development of such vein systems may be largely controlled by rock competency and geometry. Stratabound vein arrays are known to be unfavourable for mineralisation (Gillespie et al., 1999).

5.3. Shear zones and veins at North Rambull

At North Rambull, granodiorite is the only rock type present (gabbros are rare and only occur on the meter scale, so they are omitted in the analysis). The rock display strong sericite, chlorite and iron carbonate replacement. Quartz grains are a few mm large and are well preserved in the least foliated rock. Shear zones are characterized by a very penetrative foliation, lamination of quartz grains and locally by strong chlorite replacement. Shear sense indicators such as lineations, steps and drag folds are abundant; they constantly indicate dextral and sinistral strike-slip movements on NW-SE and NE-SW trending shears, respectively, and reverse movement on E-W trending shears (Figure 6a and 7e). The strike-slip shear zones define a conjugate set. The shear zones are developed in all the granodiorite body. They are a few meters to several tens of meters long; outcrops are too small to see the extent of longer structures, however interpretation on aeromagnetic map suggests they can be more than 200 m long. In the eastern area, shear zones are isolated and not branched. On the other hand, to the west, shear zones of various orientations branch to form a mesh (Figure 5b). Horsetail structures are also present. A relevant observation is that no throughgoing shear zones occur at North Rambull. All movements are coherent with a N-S compression direction.

Frequent shear veins are hosted by the shear zones, to which they are subparallel (Figure 6 and 7f). Pure extension veins are hosted by the country rock outside the shear zones; they are N-S trending steeply dipping and E-W trending gently dipping to the south. Shear zones systematically cut these veins. The largest shear veins trend NW-SE. They display great thickening at dilational jogs. Veins are filled with quartz, chlorite, ankerite and sericite; tourmaline locally occurs. Most veins contain gold. Shear veins contain foliated wall rock slivers and laminated chlorite planes, both subparallel to the vein walls (Figure 7f and 10c). Gold concentrations in veins are much more elevated (>10 g/t) to the west where shear zones form a mesh than to the east (<1 g/t) where shear zones are unconnected.

At the scale of observation, veins are very irregularly outcropping and are too widely spaced to define coherent arrays (Figure 5b). Observed vein maximum thickness is 53 cm for shear veins and 3.5 cm for pure extension veins, and maximum length is respectively 1430 cm and ~250 cm. Shear veins are much larger than pure extension veins. Shear zones are

anti-clustered, with a C_v of 0.66 (± 0.21). Bad exposure and irregular vein geometries in the Rambull area did not allow measuring vein aspect ratio.

All the structures from the Rambull area are consistent with a regional N-S compression (Figure 6). The veins have very similar orientations and parageneses in the southern and northern areas. This strongly suggests that all veins emplaced at the same time in all the Rambull area.

6. Formation setting of veins

Both at MacCormack and Rambull, synchronous development of veins, subvertical foliations and shear zones, and vein folding indicate that veins emplaced in a compressional setting at the brittle-ductile transition.

Specific failure modes occurring at MacCormack and Rambull imply different valving behaviours. On one hand, at North Rambull, shear zone hosted veins and laminated chlorite planes indicate fault-valving behaviour (Cox, 1995; Sibson et al., 1988; Robert et al., 1995). On the other hand, at MacCormack, pure extension veins are a sign of hydraulic-valving behaviour (Foxford et al., 2000). Here, hydraulic-valving behaviour is somewhat different from the definition of Foxford et al. (2000) in that veins have multiple orientations.

Fault-valving behaviour indicates shear reactivation was the dominant mechanism for vein formation at North Rambull (Sibson et al., 1988). On the opposite, hydraulic-valving behaviour at MacCormack shows that shearing or faulting did not play a role in vein formation within the Porcupine-Destor shear zone. This style of veining differs from the one present 30 km further west along the same shear zone, where shear veins indicate a fault-valving behaviour (Legault et al., 2006). However in this area, the veins are hosted by subsidiary shear zones and not by the main shear zone, the setting is thus different from MacCormack.

The tectonic setting and the modes of failure give constraints on the magnitude of the stresses (Sibson, 2004 and references therein). The mode of failure in rock is greatly influenced by the effective principal stresses which are defined as:

$$\sigma'_1 = (\sigma_1 - P_f) > \sigma'_2 = (\sigma_2 - P_f) > \sigma'_3 = (\sigma_3 - P_f) \quad (9)$$

where σ_i ($i = 1, 2, 3$) are the principal stresses.

The pore fluid factor (λ_v) is the ratio of fluid pressure to lithostatic pressure and is given by

$$\lambda_v = Pf / \sigma_v = Pf / \rho_r gz \quad (10)$$

Hydrostatic fluid pressure conditions occur at $\lambda_v \sim 0.4$ and supra-hydrostatic conditions at $0.4 < \lambda_v < 1.0$. Supra-lithostatic fluid pressure conditions are defined by $\lambda_v > 1.0$. In a compressional regime, veins form where $\lambda_v > 1.0$ (Sibson, 2004).

The presence of subhorizontal veins in both MacCormack and Rambull areas show that the fluid pressure locally exceeded the lithostatic pressure and that the effective vertical stress was negative ($\sigma'_3 < 0$) which results in $\lambda_v > 1.0$. This is consistent with the fact that veins emplaced in a compressional regime.

Pure extension failure indicates that the differential stress ($\sigma_1 - \sigma_3$) was low in both areas. At MacCormack, common hydraulic breccia textures suggest a nearly homogeneous stress tensor (Jébrak, 1997).

Orientations of the structures at MacCormack and Rambull allow estimating the orientations of the principal stresses at the time of vein formation. All structures from the Rambull area indicate σ_1 was oriented N-S (Figure 6). Dip-slip lineations on the foliation plane, reverse shear zones and subhorizontal veins indicate a subvertical σ_3 . However, sets of conjugate strike-slip shear zones and subvertical extensional-shear veins, and N-S trending steeply dipping extension veins indicate σ_3 was transiently oriented E-W at Rambull. This suggests σ_3 and σ_2 permuted.

At MacCormack, the regional σ_1 orientation may be N-S. Within the country rock, dip-slip stretching lineations and subhorizontal veins suggest the regional σ_3 orientation was subvertical (Figure 4). The local orientation of σ_1 in the vicinity of the transpressional shear zone is NW-SE, as indicated by the S2 foliation. Steeply to moderately dipping NE-SW and NW-SE trending extension veins indicate NW-SE and NE-SW orientations of σ_3 , respectively. The average orientations of σ_3 during vein formation, which is synchronous with

the local D2 deformation, suggest σ_3 permuted with σ_1 and σ_2 . Both MacCormack and Rambull vein systems may have formed during regional N-S shortening.

7. Stress in the MacCormack area

7.1. Regional stress magnitude

The vein aspect ratio was used to calculate the driving stress at MacCormack. As nearly all veins are arranged in echelon in this area, the veins were measured following the method of Nicholson and Pollard (1985) such as shown in Figure 2b, and ΔP was calculated using Eq. (7). All measured veins overlap. Systematic ratios of $L/k > 1$ and $s/k < 1$ show that no vein behaves as an isolated vein. Normalized dilation (ND) gives values of 5-6 for veins from the rhyolite and mostly 4-6 for veins from fuchsite zones. These results suggest that veins have abnormally high thickness compared to an isolated vein, a fact that is common in overlapping vein arrays (Nicholson and Pollard, 1985; Vermilye and Scholz, 1995).

Elastic properties measured in rhyolites from the Superior province give average values of 29 GPa for μ and 0.24 for ν (Coates et al., 1968; Herget and Arjang, 1990). Using these parameters with measured W , k and ND for each vein give ΔP values ranging from 19 MPa to 71 MPa, and an average ΔP of 42 MPa. This average driving stress is very close to values from the literature determined for isolated veins (Vermilye and Scholz, 1995; Mazzarini and Isola, 2007). Average ΔP is consistent with the high end of the range of tensile strengths for crystalline volcanic rocks of a few to several tens of MPa (Lockner, 1995).

To test the validity of the result, the driving stress was also calculated for veins which have a thickness approaching the thickness of an isolated vein of length L' . Using Eq. (6) give ΔP values ranging from 15 MPa to 49 MPa and an average ΔP of 34 MPa. This average value approaches the calculated driving stress of 42 MPa and thus suggests it is reliable.

The driving stress is more difficult to estimate for veins emplaced in the anisotropic foliated fuchsite-carbonate zones, because elastic properties of this rock type are unknown. However, using a μ of 6 GPa and a ν of 0.25 (Hoek, 2000) give an average ΔP of 48 MPa. For the following analysis, the driving stress for veins emplaced in the rhyolite is used.

Using a density of 2600 kg m^{-3} for rhyolite, 1000 kg m^{-3} for fluid and the average driving stress of 42 MPa in Eq. (8) give a depth formation of 2.7 km for the veins. This result is consistent with the fact that the veins cut porphyric intrusions which may have emplaced at shallow depths (Robert, 2001); it is also consistent with the low metamorphic grade of the background rocks. This depth is relatively shallow when compared to depth estimation of the ductile-brittle transition in the crust which is broadly situated at 10 km. However, the ductile-brittle transition could reach depths of a few km within phyllosilicate-rich sheared rocks, especially at slightly elevated geothermal gradients (Imber et al., 2001).

The inferred depth allows estimating the lithostatic pressure or vertical stress (σ_v) in the MacCormack area at the time of vein formation. The vertical stress, σ_3 , is 68 MPa.

Measurement from boreholes up to 9 km deep show that pore fluid factors in the upper crust are very close to hydrostatic values ($\lambda_v \sim 0.4$; Townend and Zoback, 2000). As we assume the veins in the MacCormack area emplaced at 2.7 km depth, it is inferred that the regional pore pressure in the area was hydrostatic during vein emplacement. For hydrostatic pore pressure, the regional stress parallel to the direction of compression (σ_1) during crustal shortening is assumed to be $1.6 \sigma_v$ (Mancktelow, 2008). The maximum horizontal stress (σ_1) is 109 MPa. Assuming the regional pore fluid factor of 0.4 in the MacCormack area, the regional fluid pressure would be 27 MPa.

7.2. Numerical modeling

Stress numerical modeling has been performed using UDEC (see 3.3) to test if rock rheological contrasts and geometries have an impact on the stress distribution in the rock sequence during regional compression. The approach was to determine if there is a correspondence between (1) the vein system location and the stress field and (2) the type of failure and the relative magnitude of the stresses.

The model comprises three rock types (Figure 11a): (1) crystalline rocks, which are the most competent, (2) sedimentary rocks, and (3) strongly deformed and altered rocks of the shear zone, which are the least competent. As no faulting occurred at the time of vein formation, all contacts are lithological contacts. The rock and contact properties are listed in

Table 1 and are from Oliver et al. (1990, 2001), except for rocks of the shear zone. Bulk and shear modulus for the shear zone rocks have been calculated from Hoek (2000) who estimates the Young modulus of quartz mica schist to be 10 Gpa. For a wide range of Poisson's ratio (0.1 to 0.4), the highest values of the bulk and shear modulus are ~15 MPa and ~7.5 MPa, respectively.

The average regional foliation is oriented at 75-255° and subvertical, so the maximum compressive stress (σ_1) orientation is 165-345°; its magnitude is 109 MPa (see previous section). The minimum horizontal compressive stress (σ_2) is oriented 75-255° and its magnitude is taken equal to the lithostatic stress at 68 MPa. Using higher or lower values for σ_2 give similar results. The differential stress is 41 MPa and mean stress (σ_m) is 89 MPa. As the model represents a horizontal section, the differential stress is $(\sigma_1 - \sigma_2)$ and the mean stress is $(\sigma_1 + \sigma_2)/2$.

During model run and stress propagation a large negative anomaly is generated and maintained within the shear zone. Edge effects are minor and mainly focussed on the boundaries of the model. The model shows a good correlation between low σ_1 , σ_2 , σ_m and the vein envelope location (Figure 11). This suggests the perturbed stress field was important for vein formation in the MacCormack area.

The low stress anomaly around the shear zone is the result of contrasting rock rheologies. These contrasts create a large gradient in maximum, mean and differential stress, and a smaller gradient in minimum stress. A cross-section through the low stress anomaly shows that the differential stress is 5-10 MPa in the centre of the anomaly (Figure 11b). This zone corresponds to the location of the vein envelope. Such low differential stress is highly favourable for pure extension failure (Sibson, 2004). Mean stress shows that the zone of low stress is about the size of the rheological heterogeneity, i.e. the shear zone. In this zone, mean and differential stress are about five times lower than the regional input stresses. These results are in agreement with stress drops occurring in rock sequences containing heterogeneous lithologies (Ridley, 1993; Oliver et al., 2001).

The lithostatic stress (σ_3) is not part of the model because it represents a 2D horizontal section. However, synchronous developments of subhorizontal and subvertical

veins on the field indicate that σ_3 was close to σ_1 and σ_2 in the area. This suggests that σ_3 was highly lowered around the shear zone, probably in the same manner than σ_1 and σ_2 .

The stress distribution in the rock sequence shows that stress conditions are suitable for the formation of pure extension fractures within the shear zone and its immediate host rocks.

8. Discussion

This section presents two models for vein formation along the Porcupine-Destor shear zone. The first model is for the Rambull area and the second one is for the MacCormack area. The models are then generalised to two end-member mechanisms for vein formation along a shear zone.

Shear zones and veins in the Rambull area form a mesh developing within the granodiorite layer (Figure 12a). During regional shortening, the throughgoing South Rambull shear zone, oriented at 80-90° to σ_1 , was strongly misoriented for frictional reactivation. This may have allowed the fluid pressure to build up to supralithostatic values ($\lambda_v > 1.0$), and the fault-fracture mesh to form (Sibson, 2004). Strike-slip shear zones, oriented at 50-60° to σ_1 , were the most suitable for frictional reactivation in the Rambull area (Figure 6a). Reactivation controlled shear vein formation through fault-valving behaviour. The veins indicate that the effective vertical stress was very low in the Rambull area. In such conditions, rock failure is very sensitive to rock competency, and the most competent rocks are likely to fail under a greater range of differential stress than other rocks (Sibson, 2004). Veins and shear zones are largely developed within the granodiorite, showing this rock unit was the most suitable for failure in this area. Competent gabbro layers embedded within the basalt were also the loci for failure. On one hand, the 200 m thick granodiorite layer favoured failure on a regional scale. On the other hand, the gabbro layers of a few meters thick constrained failure on the meter scale. The granodiorite largely controlled the development of the fault-fracture mesh in the Rambull area.

Fault-valving behaviour at Rambull indicates that veins emplaced in the seismogenic regime (Figure 13; Cox, 1995; Sibson et al., 1988; Robert et al., 1995). The fault-fracture

mesh geometry displays distributed valving which developed in the absence of throughgoing shear zone (Figure 12a). This implicates that the mesh self-generated and was not the product of rupture propagation along a major shear zone (Sibson, 2001). Sibson (2001) suggests this distributed type of fault-valving behaviour may correspond to earthquake swarm activity, where numerous small earthquakes occur without a distinct principal shock. However, as the fault-fracture mesh is located only at ~3 km from the Porcupine-Destor shear zone core, a major rupture event along this shear zone could account for the mesh formation. In such a scenario, aftershock triggering within the granodiorite could have favoured failure and formation of the fault-fracture mesh (Micklethwaite et al., 2010). In both scenarios, the fault-fracture mesh may have formed as a result of static stress drop within the granodiorite.

Stress numerical modeling at MacCormack suggests the vein system formation was largely controlled by a major stress drop in the shear zone area, which is the result of contrasting rock rheologies (Figure 12b). In this model, it is assumed that regional fluid pressure is hydrostatic ($\lambda_v \sim 0.4$), whereas local fluid pressure (i.e. where veins formed) is supralithostatic. The following section is subdivided in two parts: (1) stress conditions before vein formation; (2) stress conditions at the time of vein formation.

This part deals with the stress conditions before vein formation. In a deviatoric stress field, the lithostatic stress (σ_v) can be considered to be the mean stress (σ_m ; Ridley, 1993). The stress profile through the rock sequence in the MacCormack area suggests that mean stress, and thus lithostatic stress, were locally lowered close to regional hydrostatic fluid pressure values (i.e. 27 MPa; Figure 11b). When such a stress drop occurs, drop in mean stress is likely to be buffered by a drop in fluid pressure (Figure 13; Ridley, 1993). Thus, the local fluid pressure may be lower than the regional fluid pressure at the time of stress drop apparition. Ridley (1993) shows this difference in fluid pressure induces fluid flow in the zone of low pressure to equilibrate the regional fluid pressure level. At MacCormack, vein fillings indicate elements did not migrate on a large scale but rather suggest a migration on the meter scale. This strongly suggests that on a regional scale fluid pressure did not equilibrate through migration of elements, but probably through migration of an aqueous fluid. This would explain why veins are barren at MacCormack.

The local stress conditions resulted in vein formation. As the local mean stress is maintained low at the time of local fluid pressure equilibration above mean stress values, the effective stress may become negative (Ridley, 1993, Figure 5). This involves rock failure at $\lambda_v > 1.0$. Relevant in this model is that conditions for failure are attained only locally and through a dramatic stress drop and do not implicate a build up of the fluid pressure to regional lithostatic stress values. Thus, the first factor leading to vein formation is the stress drop, and not the fluid pressure level.

Relative to the timing of the low stress zone apparition, two possible scenarios may lead to vein formation: (1) the low stress zone formed at the brittle-ductile transition, allowing “instantaneous” vein formation; (2) the low stress zone created in the ductile regime, and veins formed later when deformation conditions reached the ductile-brittle transition. Strongly foliated rocks of the shear zone, folding and widespread mineral replacement in sheared rocks indicate early deformation was ductile at MacCormack. In these conditions, the geometry of the rock sequence and the relative rheological contrasts were likely to be similar to the ones present at the time of vein apparition. Thus, the low stress anomaly around the shear zone was probably already present during ductile deformation, which would account for early strong fluid fluxing responsible for mineral replacement in this zone. Later on, probably through temperature decrease, brittle deformation conditions allowed vein formation. All these features suggest the low stress anomaly at MacCormack was long-lived, favouring the second rather than the first hypothesis proposed above.

The mean stress determines volumetric strain (Sibson, 2001). The proposed model for vein formation in the MacCormack area suggests that veins formed as a consequence of equilibration between fluid pressure and mean stress when the rocks reached the ductile-brittle transition. This occurred through an increase in volumetric strain in the zone of low mean stress. This implies that all veins may have emplaced on a short time span when deformation conditions became brittle. This is consistent with observed vein textures which suggest a rapid opening (Foxford et al., 2000).

Two end-member mechanisms of stress perturbation may lead to vein formation along a shear zone. (1) Stress change generated by earthquake rupturing along the shear zone, where transient stress state allows vein formation. Such phenomenon is short lived and lasts

days to a few years; it is currently the classical coseismic model for vein formation along a shear zone (Sibson, 2001; Micklethwaite et al., 2010). (2) Stress change generated by competency contrast, where shear zone rocks represent an incompetent unit that modifies the local stress state; vein formation in such a setting is possibly related to low seismicity, i.e. non volcanic tremor (Schwartz and Rokosky, 2007). Such stress change is likely to be long lived, possibly on the order of 10^5 - 10^6 years because it is governed by regional compression duration, which may last several million years.

9. Conclusion

Veins along the Porcupine-Destor shear zone formed during regional N-S subhorizontal shortening in brittle-ductile deformation conditions. Two distinct styles of veining have been distinguished along the shear zone. The first style is located in the Rambull area, and the second one occurs 25 km away in the MacCormack area. In the Rambull area, pure extension, extensional-shear and shear veins are extensively developed. Veins are gold-bearing and are synchronous with shearing along low order shear zones. These shear zones largely developed in a granodiorite intrusion. It is the classical Sibsonian model for vein formation along a shear zone. At MacCormack, veins are barren and define a $\sim 500 \times 1000$ m envelope of pure extension veins developed in the main regional shear zone and its immediate country rocks. Veins cut and postdate the shear zone foliation and alterations. Analysis of veins indicates that they formed during local NW-SE compression and that vein filling fluid was from local origin. Statistics show that vein arrangement does not vary with rock type. On the opposite, vein shape is strongly influenced by rock type and veins have much larger dimensions in strongly foliated rocks of the shear zone.

Based on vein geometry, the average driving stress leading to vein formation at MacCormack was estimated to be 42 MPa. The corresponding depth of formation for veins is 2.7 km. This depth agrees with the fact that background rocks in the region are weakly to none deformed and metamorphosed, and that veins cut porphyric intrusions which may have emplaced at shallow depths.

Both at MacCormack and Rambull veins formed as a result of supralithostatic fluid pressure level. At Rambull, strong fluid overpressuring results in coseismic failure during the fault-valve cycle. On the opposite, at MacCormack competency contrast leads to a major drop in the tectonic stress, which drives failure in the postseismic regime. These two end-member mechanisms of stress modification are expected to form veins along shear zones.

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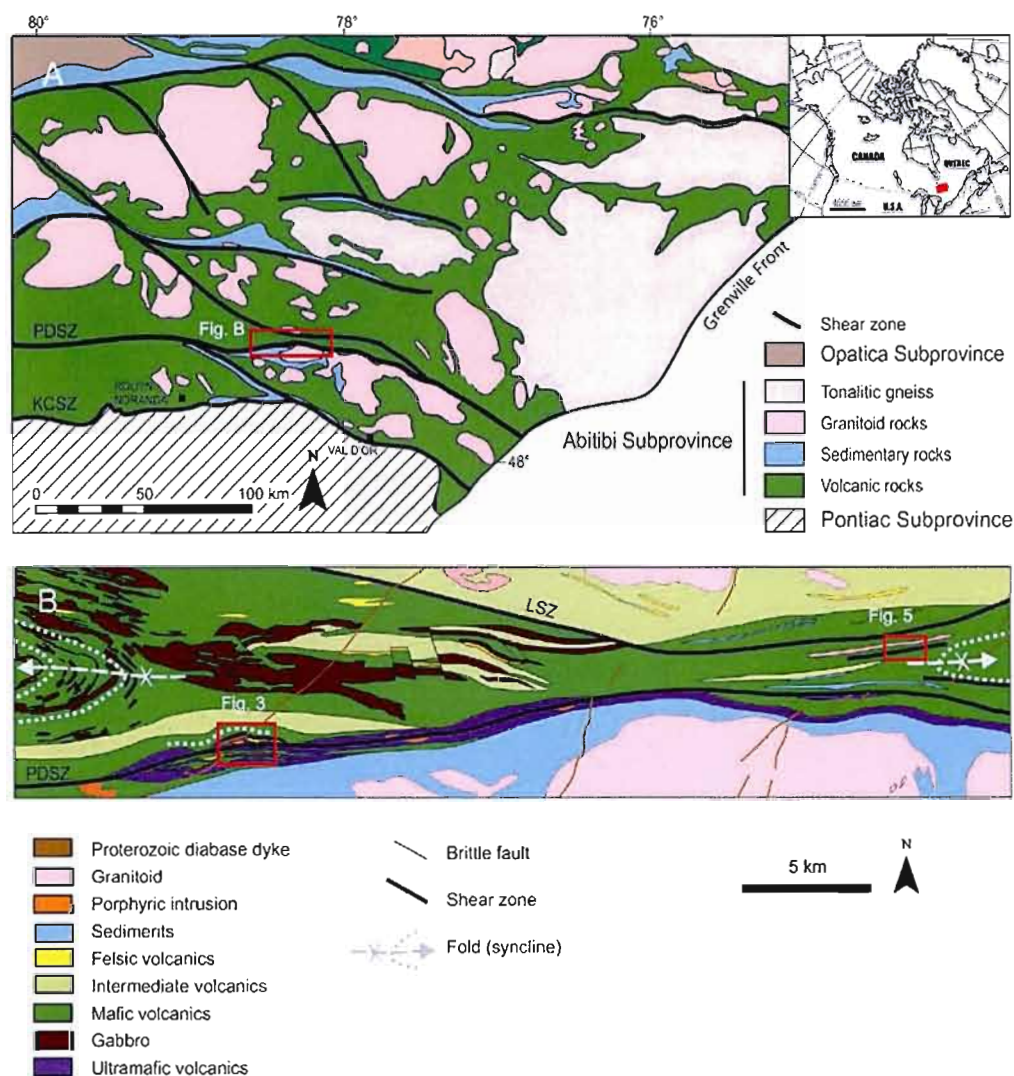


Figure 1. (a) Simplified geology of the Southeastern Abitibi greenstone belt (modified from Mueller et al., 1996). The rectangle indicates the location of figure b. PDSZ, Porcupine-Destor Shear Zone; KCSZ, Kirkland-Cadillac Shear Zone. (b) Simplified geology of the Kinojevis area (modified from Pilote et al., 2008). The rectangles indicate the two studied areas. LSZ, Lyndhurst Shear Zone.

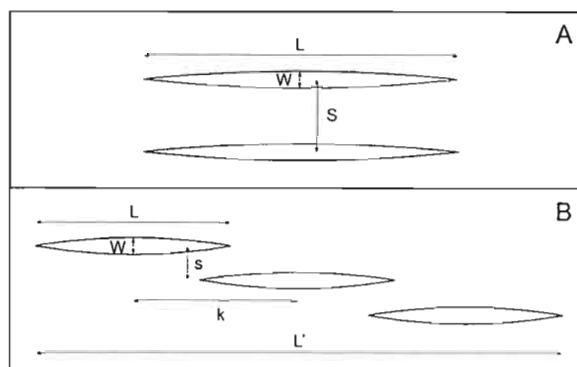


Figure 2. Methods to measure the geometric features of veins for isolated veins (a) and in echelon veins (b) (modified from Nicholson and Pollard, 1985). k , centre spacing; L , vein length; L' , in echelon vein array length; s , local spacing between in echelon veins; S , spacing between veins; W , vein thickness.

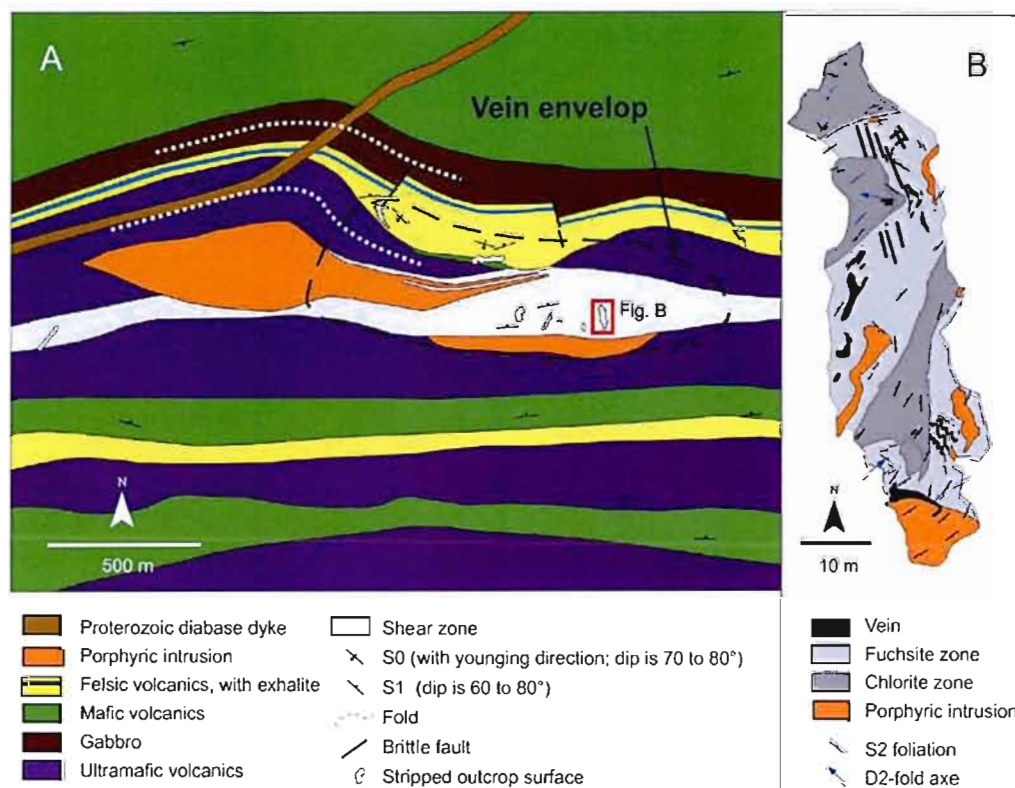


Figure 3. (a) Geology of the MacCormack area, with the position of the vein envelope indicated. The rectangle indicates the location of figure b. (b) Geology of a stripped outcrop within the shear zone. S1 foliation is parallel to the contacts between the fuchsite and the chlorite zones and is folded by the NE trending S2 foliation.

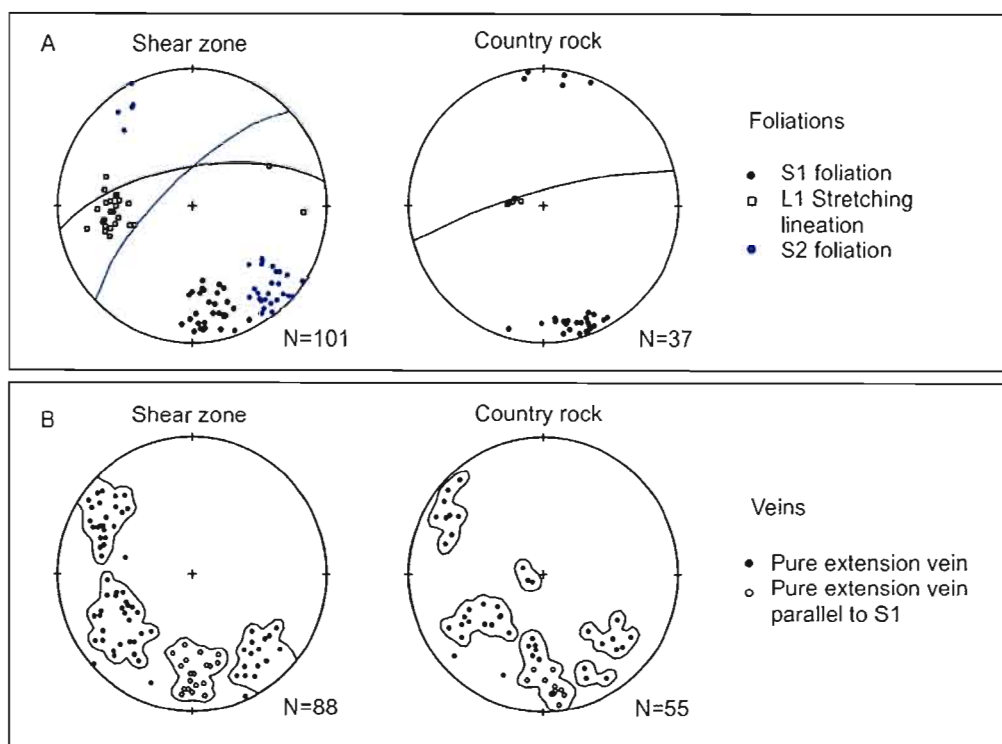


Figure 4. Orientation of foliations (a) and veins (b) in the MacCormack area. The structures presented here have preserved their initial orientations and were not affected by the F2 folding event. Stereonets are lower hemisphere, equal area. Great circles indicate the average orientation of foliations.

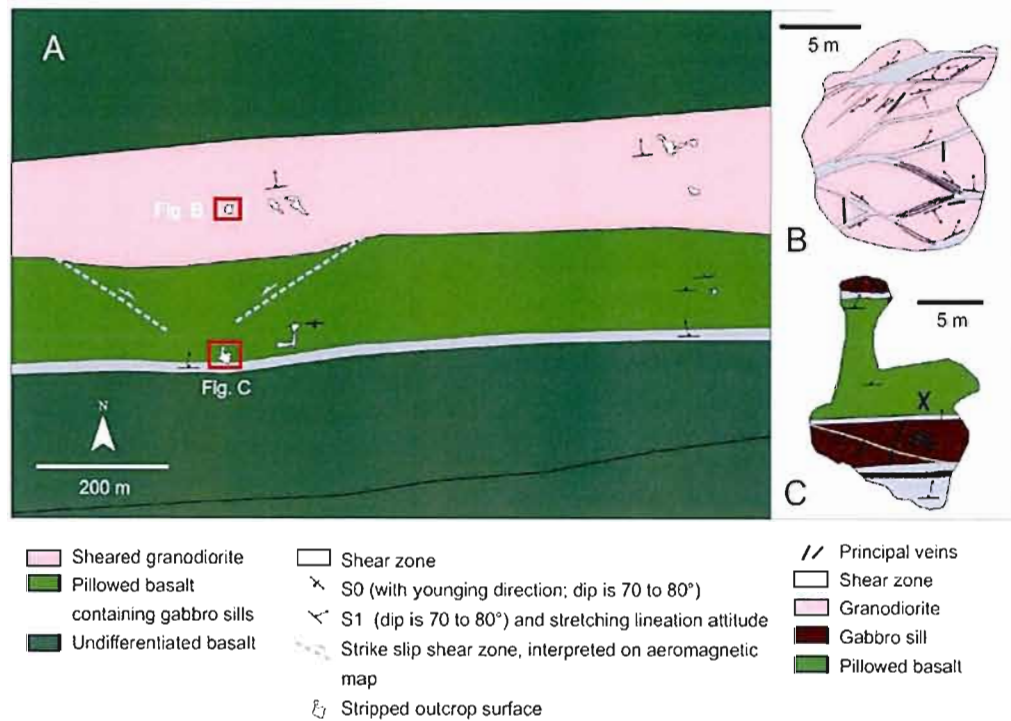


Figure 5. (a) Geology of the Rambull area. The rectangles indicate the location of figures b and c. (b) Geology of a stripped outcrop from the North Rambull area. (c) Geology of a stripped outcrop from the South Rambull area.

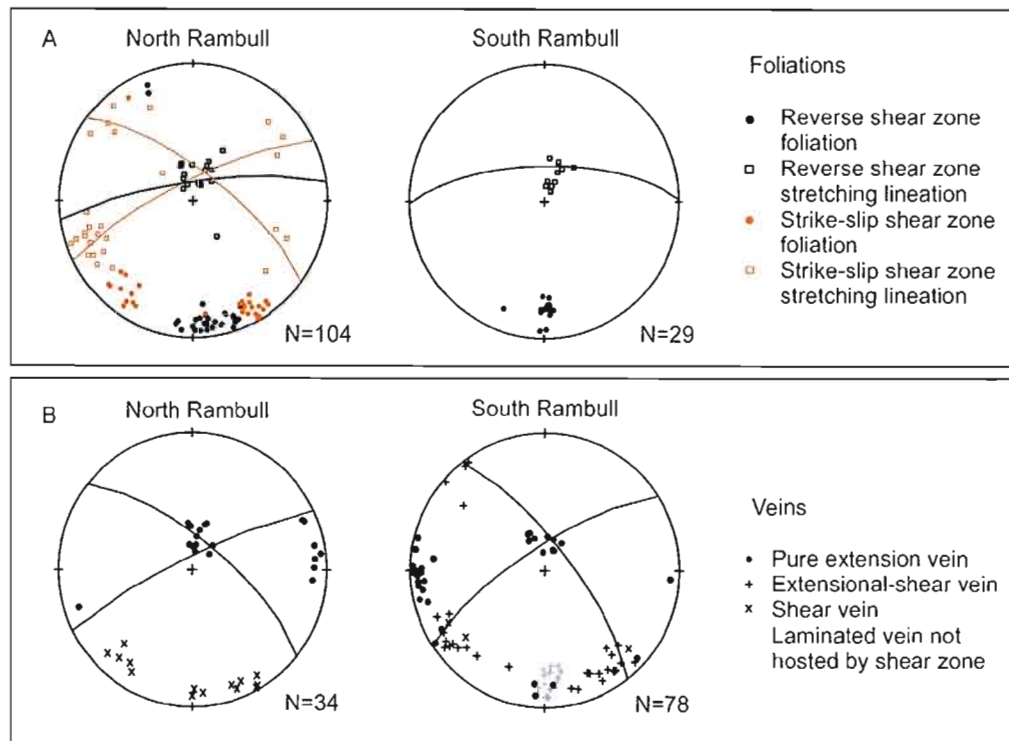


Figure 6. Orientation of foliations (a) and veins (b) in the Rambull area. Stereonets are lower hemisphere, equal area. (a) Great circles indicate the average orientation of shear zones and conjugate sets of strike slip shear zones. (b) Great circles indicate the average orientation of conjugate sets of shear veins at North Rambull and extensional-shear veins at South Rambull.

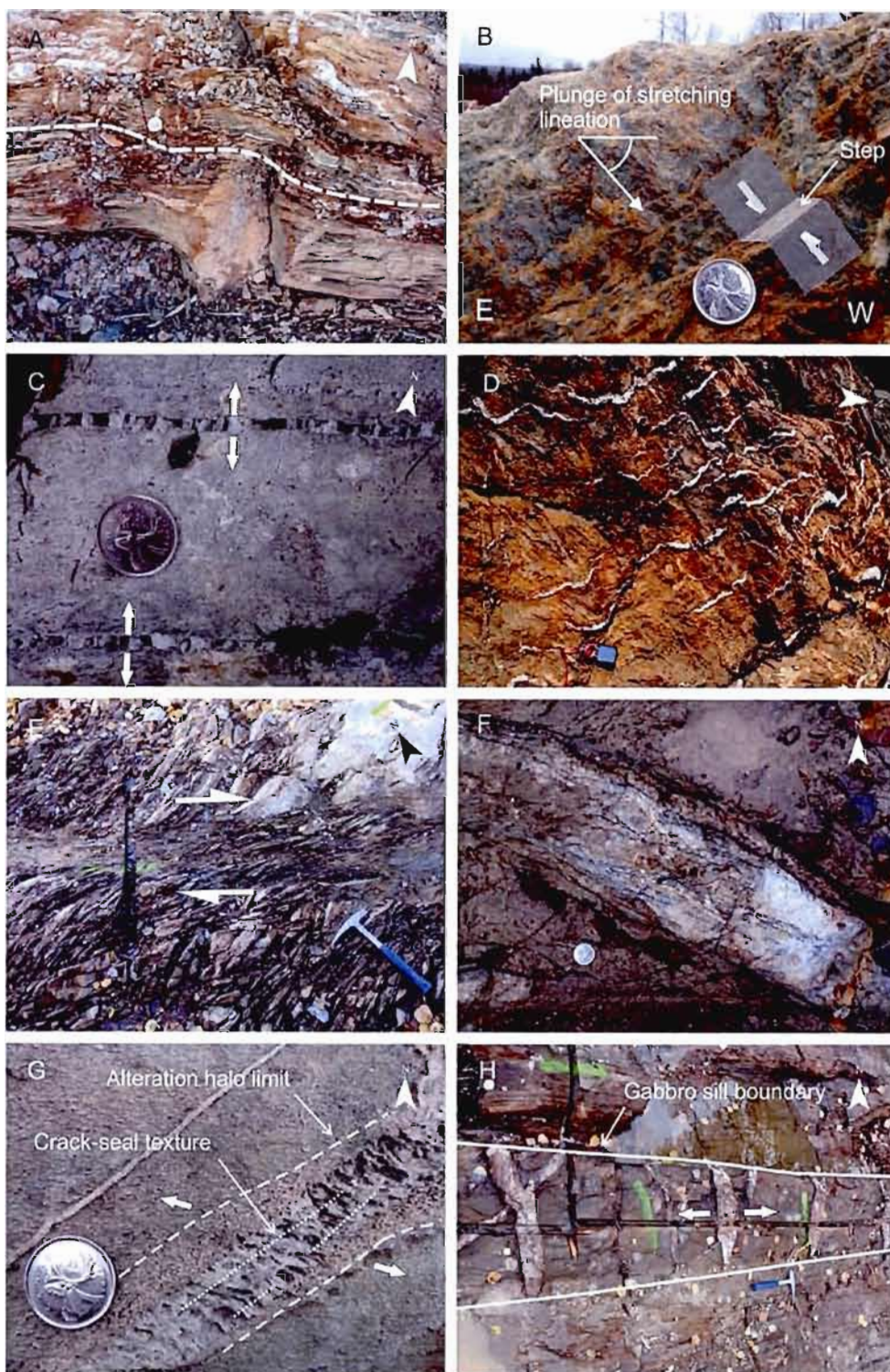


Figure 7. Photographs of structures at MacCormack (a-d), North Rambull (e-f) and South Rambull (g-h). (a) Slightly folded foliation in the fuchsite-iron carbonate zone. Coin for scale. (b) Vertical view showing the plunge of the stretching lineation. Brittle steps suggest a dextral reverse movement. (c) Pure extension veins within the country rock (rhyolite). Arrows indicate direction of vein opening. (d) Array of slightly folded pure extension veins within the shear zone, in the fuchsite-iron carbonate zone. Note the veins are regularly spaced and unconnected. Veins are folded by the D2 deformation. Compass for scale. (e) Dextral shear zone developed in the foliated granodiorite. Note the C-S fabric. (f) Shear vein hosted by a discrete brittle-ductile shear zone in the granodiorite. Dark lines within the white quartz and parallel to the vein walls are chlorite planes. (g) Extensional-shear vein with quartz fibres crystallised obliquely to the vein walls. The vein exhibits a crack-seal texture. An alteration halo borders the vein. Host rock is a gabbro. Thick arrows indicate direction of vein opening. (h) Stratabound vein array developed in a gabbro sill surrounded by strongly foliated basalt. Note the regular spacing of veins.

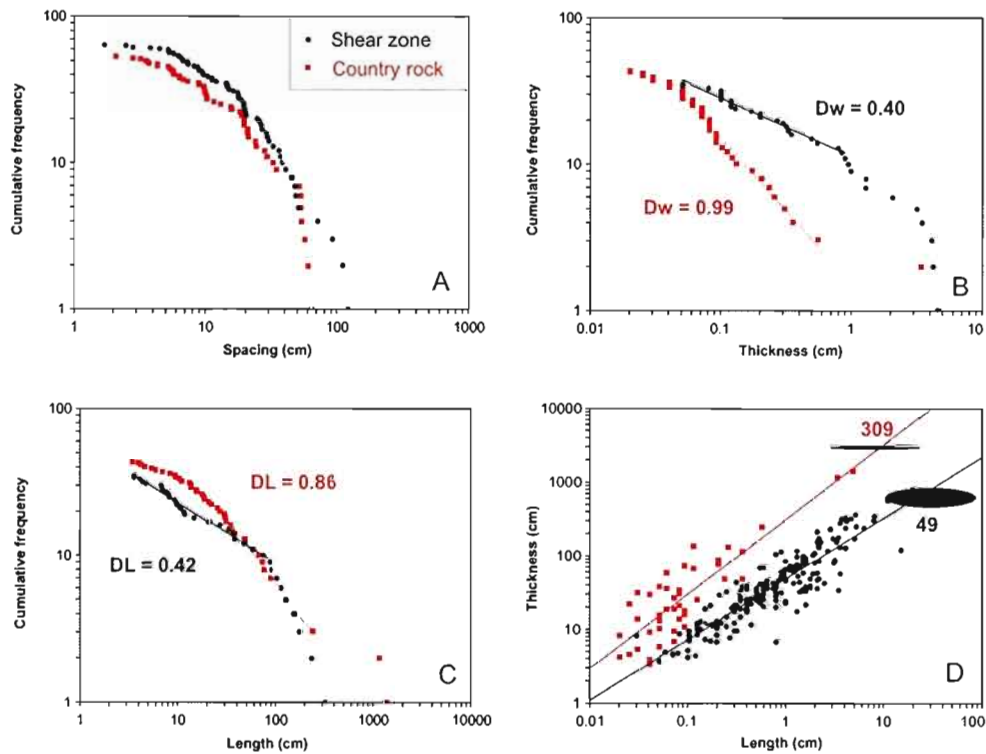


Figure 8. Statistic distributions of vein geometric parameters at MacCormack for veins from the shear zone and the country rock. (a) Cumulative frequency distribution of vein spacing. (b) Cumulative frequency distribution of vein thickness. (c) Cumulative frequency distribution of vein length. (d) Plot of vein length vs vein thickness. Schematic vein shape and average length/thickness ratio are indicated. DL and Dw are the slopes of the curves for vein length and vein thickness distributions, respectively.

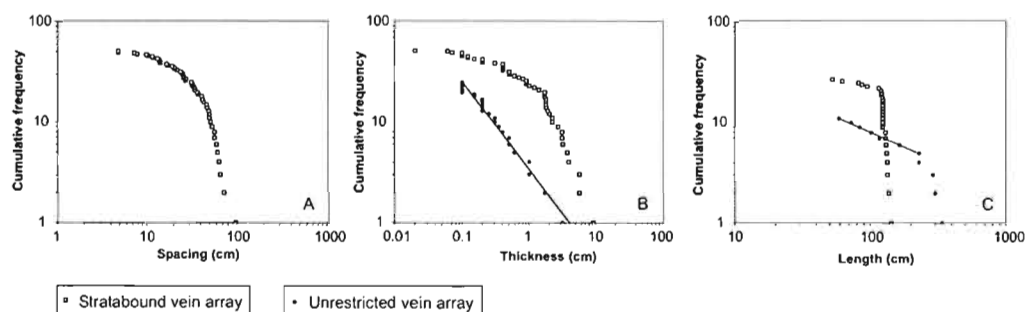


Figure 9. Statistic distributions of vein geometric parameters at South Rambull for a restricted stratabound vein array and for an unrestricted vein array. (a) Cumulative frequency distribution of vein spacing. (b) Cumulative frequency distribution of vein thickness. (c) Cumulative frequency distribution of vein length.

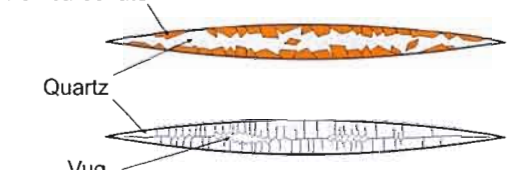
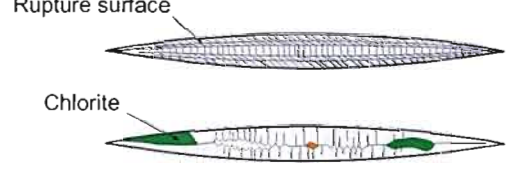
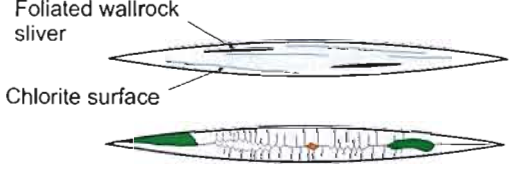
A MacCormack area 	Host rock Shear zone Country rock	Type of failure Pure extension Pure extension
B South Rambull area 	Host rock Country rock Country rock	Type of failure Extensional-shear Pure extension
C North Rambull area 	Host rock Shear zone Country rock	Type of failure Shear Pure extension

Figure 10. Vein textures at MacCormack (a), South Rambull (b) and North Rambull (c). Columns on the right show if veins are hosted by shear zones or their country rock and the type of failure associated with each vein type.

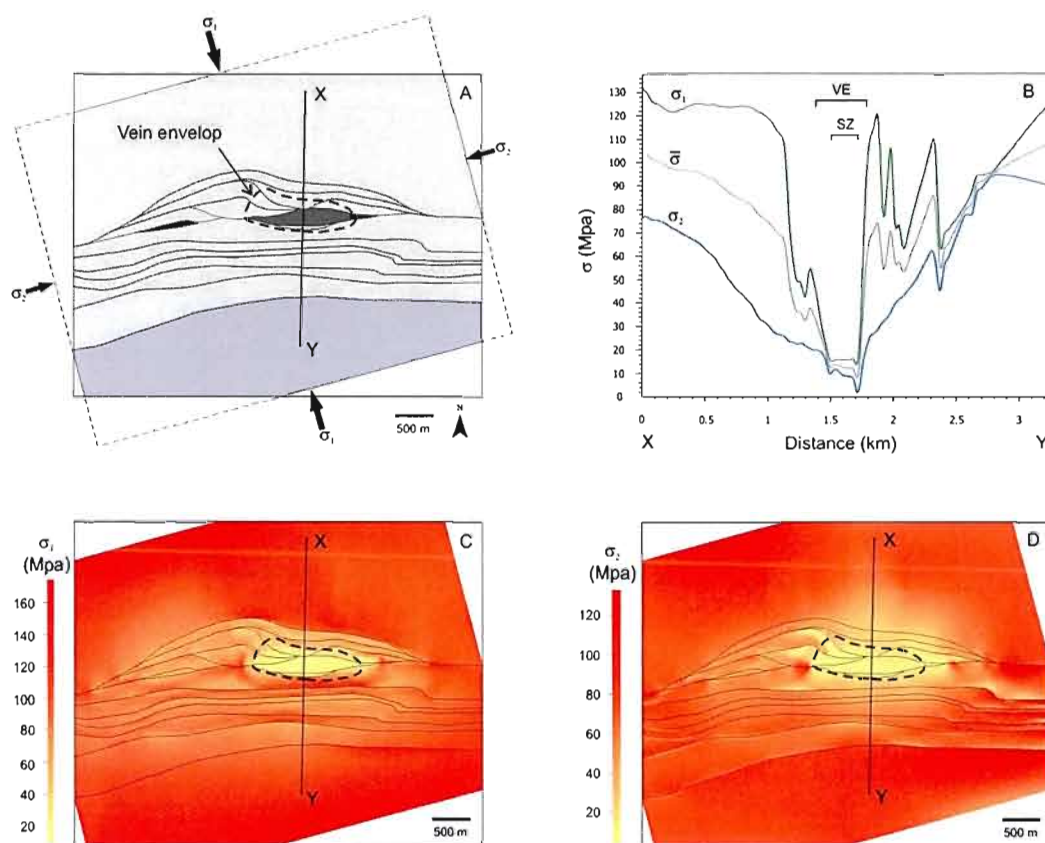


Figure 11. Udec modeling in the MacCormack rock sequence. (a) Input geometry of the model. The geology is simplified to three rock types: crystalline rocks, light grey; sedimentary rocks, medium grey; and sheared altered rocks, dark grey; and one type of contact. Properties are listed in Table 2. Stress orientation and magnitude represent the inferred regional stress field at the time of vein formation (see text). (b-d) Stresses after 1040 cycles. (b) Cross-section of the maximum, minimum and mean stresses through the rock sequence. SZ and VE indicate the position of the shear zone and the vein envelope, respectively. (c) Contours of the maximum compressive stress, σ_1 . (d) Contours of the minimum horizontal compressive stress, σ_2 . A low stress anomaly is centred on the shear zone, and stresses are the lowest within the shear zone. The low stress anomaly shows a good spatial correlation with the vein envelope. Note the differential stress is very low in the centre of the anomaly.

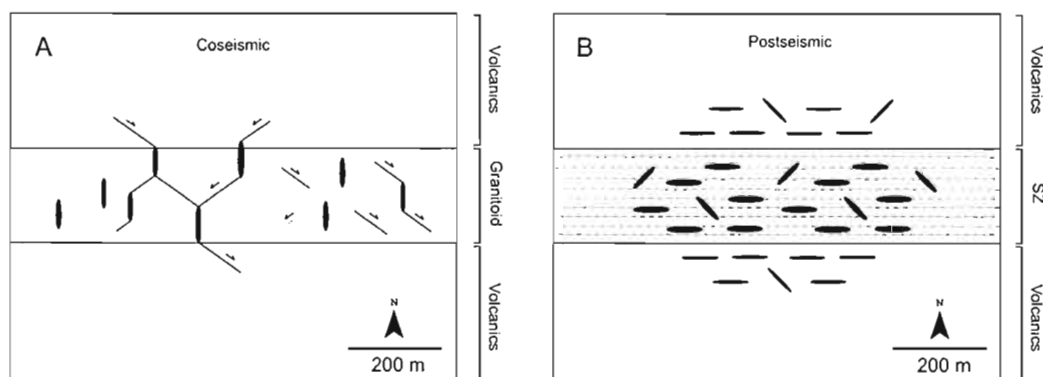


Figure 12. Two veining mechanisms along the Archean Porcupine-Destor shear zone. (a) Coseismic fault-valving behaviour through formation of a fault-fracture mesh at Rambull. Vein formation is largely controlled by faulting or shearing (partly from Sibson, 2001). (b) Postseismic hydraulic-valving behaviour through formation of fracture arrays at MacCormack. Vein formation is mainly controlled by competency contrast between sheared and intact rocks. SZ, shear zone. Veins are not to scale.

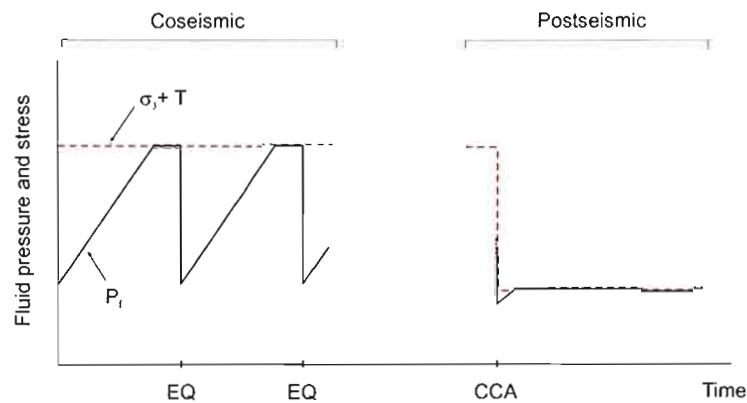


Figure 13. Schematic illustration of evolution of fluid pressure (P_f) and minimum compressive stress (σ_3) with time along the Porcupine-Destor shear zone. Conditions for failure are attained when fluid pressure equals $\sigma_3 + T$, where T is the rock tensile strength. Fault-valving behaviour promotes strong cyclic variation of the fluid pressure during earthquake rupturing (EQ) in the seismogenic regime. In the postseismic regime, competency contrast between shear zone rocks and intact country rocks promote strong drop in the minimum compressive stress (CCA), which is approximated to instantaneous. At that time fluid pressure lowers to buffer the stress drop. Then fluid pressure increases to equilibrate to the regional fluid pressure level, and conditions for failure are attained and maintained, without significant cyclic variation.

Table 1. Statistics of vein geometric features

	Number of veins	Number of line samples	Max. W (cm)	Max. L (cm)	Average L/W ratio	Average e (%)	Max. S (cm)	Average S (cm)	Average C _v	Average d (vein/m)
MacCormack shear zone	283	12	350	>1230	49	10.3 ± 4.7	121	16	0.76 ± 0.15	6.8 ± 4.8
MacCormack country rock	57	4	4.7	1363	309	2.2 ± 1.2	64.7	18.6	0.83 ± 0.21	6.4 ± 3.0
South Rambull	167	6	15.2	530		5.8 ± 4.8	170.5	39.6	0.66 ± 0.09	3.8 ± 3.7

W, vein thickness; L, vein length; e, extensional strain; S, vein spacing; C_v, coefficient of variation of vein spacing; d, vein density.

Table 2. Rock and contact properties for the UDEC model presented in Figure 11. Bulk and shear modulus for shear zone rocks are calculated from Hoek (2000; see text). Other parameters are from Oliver et al. (1990, 2001).

	Crystalline rocks	Sedimentary rocks	Shear zone rocks	Lithological contact
Density (kg/m ³)	2850	2850	2850	
Bulk modulus (Mpa)	50e3	40e3	15e3	
Shear modulus (Mpa)	25e3	20e3	7.5e3	
Tensile strength (Mpa)	4	3	3	0
Cohesion (Mpa)	4	4	4	0
Friction angle	35°	31°	31°	22°
Normal stiffness (Mpa)				5
Shear stiffness (Mpa)				2e-4

CONCLUSION GÉNÉRALE

L'approche méthodologique consistant à étudier en détail la géométrie des systèmes de veines et leurs implications sur les conditions géomécaniques au moment de leur mise en place a été définie au début de la maîtrise par M. Jébrak. L'objectif du projet était de mettre au point de nouveaux critères de reconnaissance de minéralisations associées à des systèmes de veines et de mieux comprendre l'architecture des failles majeures de l'Abitibi. Le travail sur le terrain menant aux descriptions géologiques, l'application de la méthodologie, la modélisation des contraintes, et la discussion qui s'en suit ont été réalisés par l'étudiant Raphaël Doutre. Le mémoire a entièrement été rédigé par R. Doutre. Les relectures par M. Jébrak ont apporté des corrections et quelques remaniements dans le texte.

Le long de la zone de cisaillement Porcupine-Destor, les veines se sont mises en place lors d'une phase de compression régionale orientée N-S, à la transition fragile-ductile. Deux styles structuraux distincts sont associés aux veines le long de la zone de cisaillement. Le premier style est localisé dans le secteur Rambull et le deuxième dans le secteur MacCormack, à 25 km à l'ouest. Dans le secteur Rambull, des veines d'extension pure, hybrides et de cisaillement sont développées. Ces veines sont aurifères et contemporaines aux cisaillements subsidiaires qui se sont largement développés dans une intrusion de granodiorite. C'est le modèle Sibsonien classique de formation des veines le long d'une zone de cisaillement. À MacCormack, les veines d'extension pure définissent une enveloppe d'environ 500x1000 m qui s'est formée dans la zone de cisaillement et ses roches encaissantes immédiates. Les veines recoupent la zone de cisaillement et les altérations et sont stériles. L'analyse des veines montre qu'elles se sont mises en place lors d'une phase de compression locale orientée NW-SE, et que les fluides sont d'origine locale. Les statistiques montrent que la disposition des veines ne varie pas en fonction du type de roche, par contre la forme des veines change de façon importante d'une roche à l'autre, et les veines sont beaucoup plus épaisses dans les roches très foliées.

La géométrie des veines a permis d'estimer la surpression de fluide moyenne à 42 MPa à MacCormack, ce qui correspond à une profondeur de formation de 2.7 km. Cette faible profondeur est cohérente avec le fait que les roches de cette région sont très faiblement déformées et métamorphisées, et que les veines recoupent des intrusions porphyriques qui se sont probablement mises en place à de faibles profondeurs.

À MacCormack et à Rambull, la formation des veines résulte d'une pression de fluide supralithostatique. À Rambull, la forte surpression de fluide est responsable de la fracturation pendant le fonctionnement cyclique de failles-valves en régime co-sismique. À l'opposé, à MacCormack le contraste de compétence des roches crée une forte diminution locale de la contrainte tectonique, ce qui provoque la rupture de la roche en régime post-sismique. Ces deux mécanismes de perturbation de la contrainte sont favorables à la formation de veines le long des zones de cisaillement.