Structural evolution of the Alaska Juneau lode gold deposit, southeastern Alaska

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The Alaska Juneau lode gold deposit is hosted by a series of polydeformed Permian to Late Triassic volcanic, pelitic, volcaniclastic, and mafic intrusive rocks. Rocks in the mine area have been sheared and metamorphosed to greenschist grade. Interpretation of rock fabrics indicates several generations of ductile and brittle deformation. Prior to mineralization, reverse shear occurred along northwest-striking and northeast-dipping ductile shear zones. Mineralization consists of Eocene auriferous quartz–carbonate veins, which cut the regional metamorphic fabrics. Mineralization was followed by reverse right-lateral shear along northwest-trending ductile–brittle shear zones. Two northwest-striking and steeply dipping vein sets host the bulk of the ore. Orientation of carbonate fibers within the quartz veins were used to determine the deformation regime that existed during mineralization. Plunge of the fibers indicate that down-to-the-northeast extension occurred synchronous with mineralization. Structural data support a model whereby the Alaska Juneau deposit formed after the peak of ductile deformation during a period of local extension. Localization of veins to areas of infolded phyllite and gabbro suggests that competency contrasts within host rocks enhanced vein emplacement. Veining may have been facilitated by a change from a contractional to a transpressive deformational regime which may have led to local extension and fluid migration to favorable deposition sites.

Le gite d'or filonien de Juneau, Alaska, est encaissé dans une série de roches volcanique, pélitique, volcanoclastique et mafique intrusive polydéformée du Permien au Trias tardif. Les roches des environs de cette mine ont été cisaillées et métamorphisées au degré des schistes verts. L'interprétation de la fabrique des roches révèle plusieurs générations de déformation ductile et fragile. Un cisaillement inverse le long des zones de cisaillement ductile, de direction nord-ouest et de pendage nord-est, a précédé la minéralisation. Le dépôt est représenté par des filons aurifères d'âge éocène, formés de quartz–carbonates, qui recoupent les fabriques métamorphiques régionales. La minéralisation fut suivie d'un cisaillement latéral-dextre inversé, le long des zones de cisaillement ductile–fragile. Deux séries de filons de direction nord-ouest et de pendage abrupt portent la majeure partie de la minéralisation. Les orientations des fibres de carbonates au sein des filons de quartz ont été utilisées pour déterminer le régime de déformation associé à la minéralisation. La plongée des fibres indiquent qu'au nord-est il y avait contemporanéité d'extension et de minéralisation. Les observations structurales supportent un modèle, dans lequel le gîte de Juneau ne fut formé qu'après la phase culminante de déformation ductile, durant une période d'extension locale. La présence de filons dans les zones de phyllite et gabbro enveloppés suggère que la mise en place des filons fut favorisée par les contrastes de compétence au sein des roches-hôtesses. La formation des filons fut probablement facilitée par le changement de régime de déformation, passant de contraction à transpression, créant ainsi l'extension locale et la venue des fluides minéralisants dans les sites privilégiés.

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Introduction

The Alaska Juneau (AJ) deposit is located near the center of the 200 km long Juneau gold belt (Fig. 1). The Juneau gold belt has produced over 211 t gold and 62 t silver from a series of mesothermal gold-quartz vein deposits. The AJ mine has been the largest lode gold producer in Alaska. Total production from the AJ mine is 102.6 t Au, 62 t Ag, 14 928 t Pb, and 141 t Cu. Over 91 Mt of ore has been milled at an average gold grade of 1.5 g/mt (Twenhofel 1960; AJ Annual Report, unpublished data, 1943). Ore bodies consist of swarms of closely grouped, gold-sulfide quartz veins that extend for over 4.5 km alongstrike and 1050 m downdip.

In general, mesothermal gold vein deposits are considered to occur in tectonically active areas of subhorizontal compression or transpression (Sibson 1990). Interpretation of structural data from the AJ mine area (this study) indicates that a compressive stress regime existed prior to and after mineralization, but the geometries of auriferous quartz veins and their internal fabrics indicate that a down-to-the-northeast extensional regime prevailed during the mineralization event.

Documentation of extension is rare in the Coast Mountains. Crawford *et al.* (1987, 1989) suggested that extension may have occurred during uplift (85–55 Ma) along the Work Channel Lineament in the Prince Rupert area of British Columbia, and Gehrels and McClelland (1988) noted evidence for uplift and down-to-the-northeast extension in central southeastern Alaska during Paleocene to Middle Eocene time (66–50 Ma). Because the age of mineralization is constrained by Ar–Ar and K–Ar dating (55 Ma, Goldfarb *et al.* 1987), as well as by the crosscutting geometries of the structures (this study), the veins at the AJ mine provide a unique opportunity to assess the relationship of veining to the stress regime.

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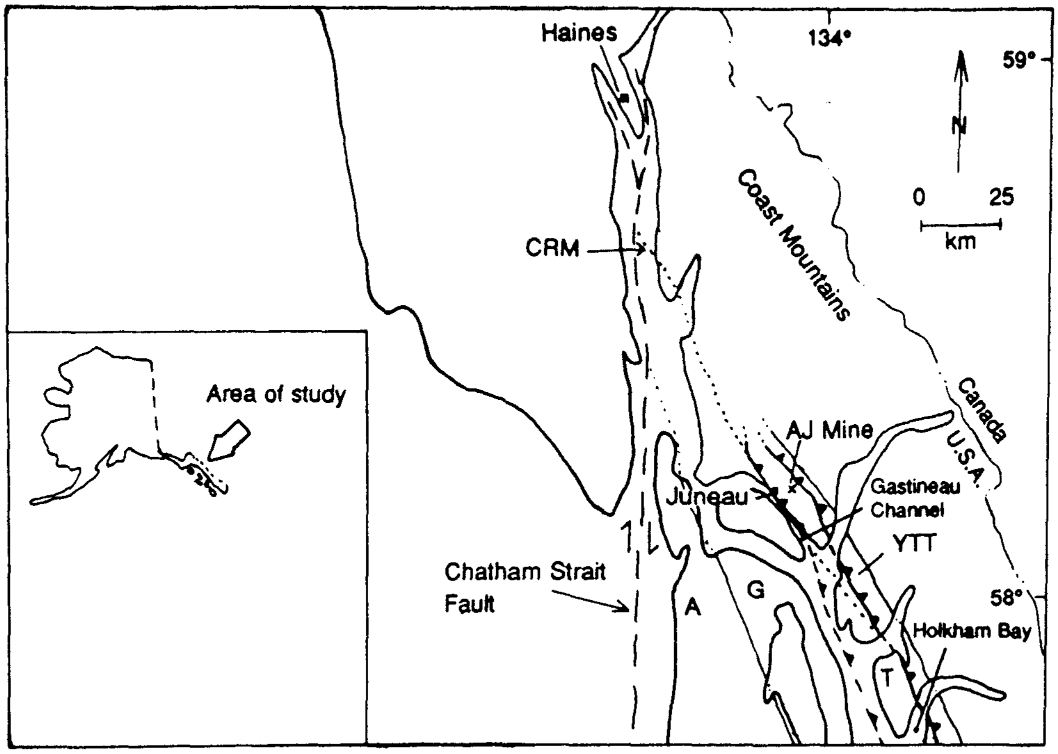

FIG. 1. Location map of the Alaska Juneau mine, showing the distribution of terranes and major structures. CRM, Coast Range megalineament (Brew and Ford 1978); YTT, rocks correlated with the Yukon Tanana terrane; T, Taku terrane; G, Gravina belt; A, Alexander terrane. After Monger and Berg (1987) and Gehrels *et al.* (1990).

Regional geology

Southeastern Alaska is composed of several lithotectonic terranes, which have been described by Monger and Berg (1987) and Gehrels and Berg (1988) (Fig. 1). The Juneau gold belt lies 2 – 10 km west of the Cretaceous to Paleogene Coast Mountains batholith. Mineralization in the gold belt is hosted by a series of polydeformed and metamorphosed submarine volcanic, pelitic, volcaniclastic, mafic intrusive, and subordinate carbonate rocks (Buddington and Chapin 1929). The AJ deposit is hosted by Permian and Triassic rocks of the Taku terrane (Gehrels and Berg 1988). Taku rocks are fault bounded to the west and the east by the mid-Cretaceous Fanshaw and Sumdum faults, respectively (Gehrels *et al.* 1992). To the west of the east-dipping Fanshaw fault are Jurassic and Cretaceous volcanic and sedimentary rocks of the Gravina belt (Gehrels and Berg 1988). The Alexander terrane lies to the west of the Gravina belt. East of the AJ deposit, the east-dipping Sumdum fault juxtaposes Taku terrane rocks with Permian and older quartz-rich metasedimentary and metavolcanic rocks correlated by Gehrels *et al.* (1992) with rocks of the Yukon – Tanana terrane. In southeastern Alaska the Fanshaw and Sumdum faults are part of an extensive system of mid-Cretaceous thrust faults identified by Crawford *et al.* (1987), Gehrels *et al.* (1990), McClelland *et al.* (1990), and Rubin *et al.* (1990).

Metamorphic grade in the Juneau area ranges from prehnite – pumpellyite facies a few kilometres west of the AJ deposit to amphibolite facies a few kilometres to the east (Dusel-Bacon *et al.* 1991). Rocks hosting the deposit are of upper greenschist grade. Apparent east-dipping isograds indicate that the metamorphic sequence is inverted (Himmelberg *et al.* 1991).

An important characteristic of the regional geology of the Juneau gold belt is the northwest trend of major structural and lithologic elements. Rock units and structures dip moderately to steeply northeast. In some parts of the region this orientation has been attributed to macroscopic isoclinal folding (Ford and Brew 1973; Forbes and Engels 1976). Northwest-striking structural elements have been disrupted by younger north-northwest-striking structures, including the Chatham Strait fault approximately 12 km west of Juneau (Fig. 1). This fault has an estimated 230 km of dextral offset (Lathram 1964; Hudson *et al.* 1982) and joins the Denali fault 50 km north of the AJ mine in the Haines area (Hudson *et al.* 1982).

The AJ mine and other quartz vein deposits in the Juneau gold belt lie within 8 km of a major topographic feature originally termed the Coast Range lineament (Twenhofel and Sainsbury 1958). This feature has been more fully defined and named the Coast Range Megalineament (CRM) by Brew and Ford (1978) (Fig. 1). In the Holkham Bay area, 64 km south of Juneau, the Sumdum thrust of Gehrels *et al.* (1992) roughly coincides with the CRM zone as defined by Stowell and Hooper (1990). West of the AJ deposit the Fanshaw fault and the CRM occupy Gastineau Channel.

In 1990 an Echo Bay mines exploration drill hole completed beneath Gastineau Channel near Juneau revealed over 400 m of tightly folded and locally mylonitic phyllite and chlorite schist which dips to the east. Minor folds are asymmetric and are crosscut by closely spaced (<10 cm wide) shear zones. The geometry of the folds reveals a reverse sense of shear. Stowell and Hooper (1990) have documented ductile reverse shearing about 64 km southeast of the AJ deposit, near the CRM (roughly correlative with the Sumdum fault) beginning at 90 Ma, followed by dextral strike-slip shearing along ductile shear zones from 90 to 60 Ma. Stowell (1987) suggested a late Tertiary age for the most recent deformation near the CRM. Farther south, in the Prince Rupert area, Crawford *et al.*

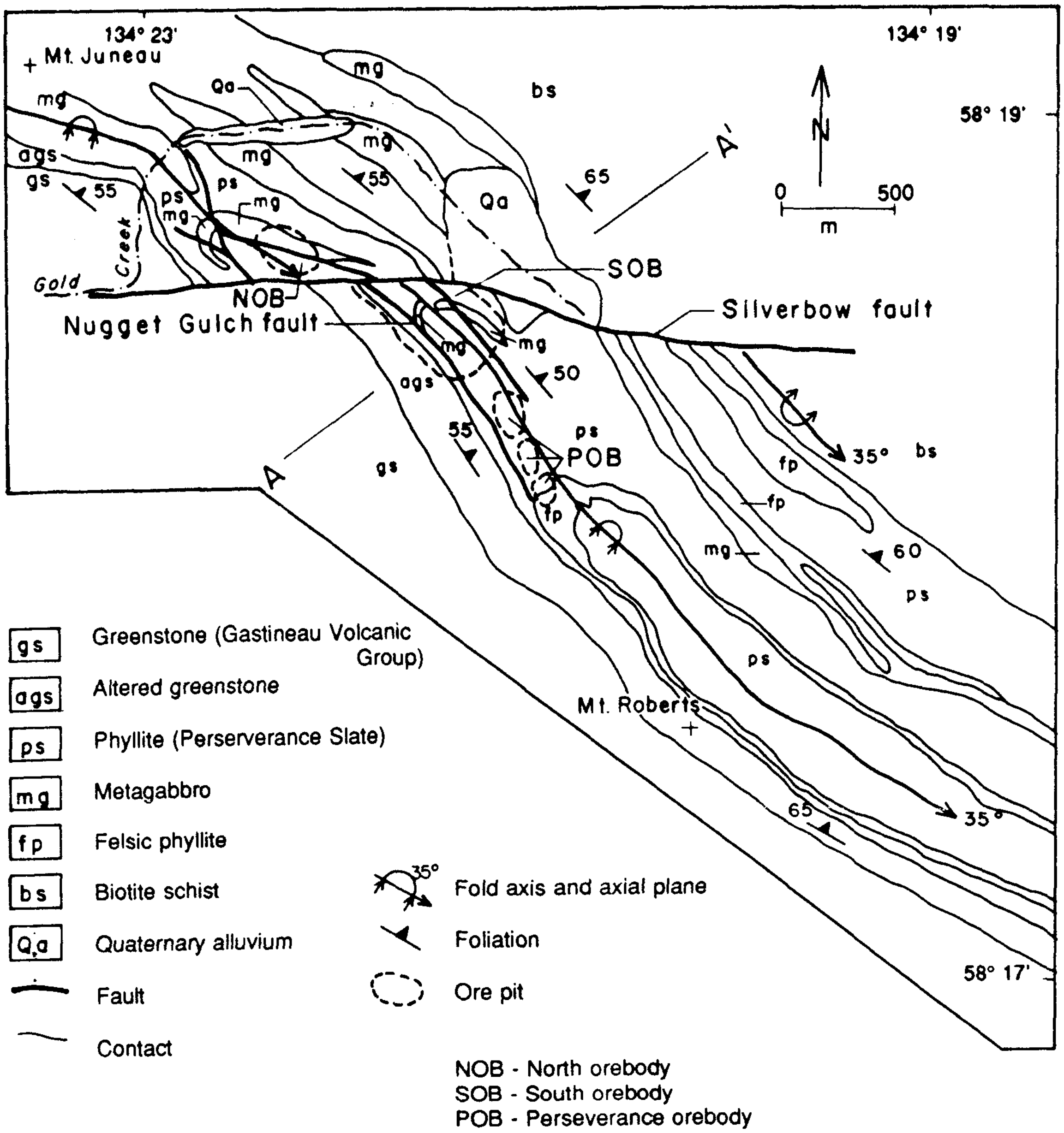

FIG. 2. General geologic map of the AJ mine area (from Werneke 1932 and this study).

(1987) have cited the offset of metamorphic assemblages along the Work Channel Lineament as evidence supporting greater than 9.6 km of vertical displacement along this steeply east-dipping shear zone during the early Tertiary. This structure has been cited by some workers as the southern extension of the CRM. Recent work in the Juneau area (this study; Gehrels *et al.* 1990; Stowell and Hooper 1990) supports a northeast-over-southwest sense of movement in mid-Cretaceous to early Tertiary time along mesoscopic and regional structures. This sense of shear correlates well with the inferred high angle of convergence between the Pacific basin and North American plate at this time (Engebretson *et al.* 1985).

Geology of the mine area

The AJ orebody is mostly hosted by a black phyllite unit of Triassic age (Brew and Ford 1977), named the Perseverance Slate (Martin 1926; Twenhofel 1960) (Fig. 2). Sill-like bodies of metagabbro within the Perseverance Slate host most of the ore. Some mineralization is also localized near the contact of the black phyllite and an infolded felsic phyllite unit. A Triassic age has been assigned to the Perseverance Slate based on Late Triassic fossils collected by Martin (1926) and Late Triassic conodonts recovered by Gehrels *et al.* (1992). Volcanic strata of the Gastineau Volcanic Group structurally and stratigraphically underlie the Perseverance Slate (Martin 1926; Twenhofel 1960). Permian conodonts have been recovered from carbonate lenses within the volcanic rocks (Gehrels *et al.* 1992) resulting in the assignment of these rocks to the Gastineau Group. The Gastineau Group consists of basaltic volcanic flows, breccias, and tuffs (Gehrels *et al.* 1992). Lithologic contacts strike northwest and dip moderately to steeply northeast.

The vein swarms constituting the orebody are located near the contact of the phyllite and gabbro–greenstone rocks, as well as within the underlying greenstones of the Gastineau Group. Where veining occurs within the Gastineau Group extensive biotite–carbonate alteration has resulted in a map-

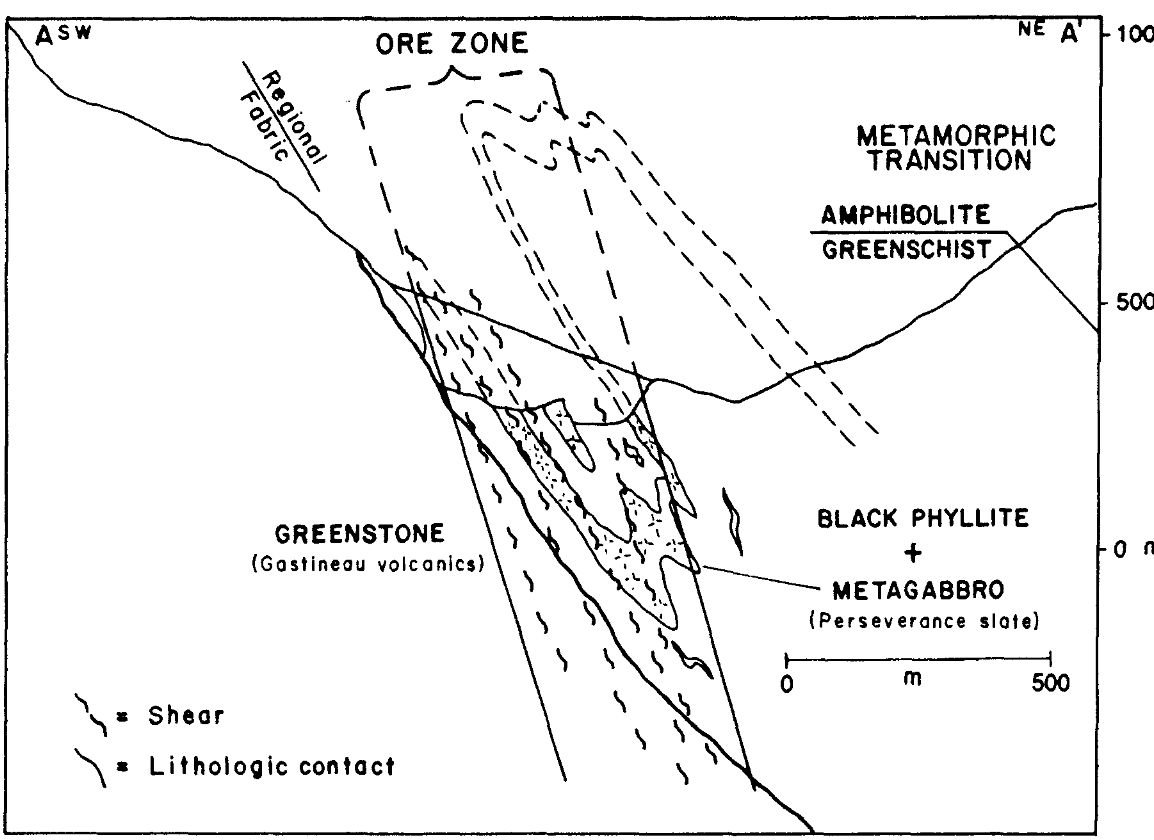

FIG. 3. Schematic cross section through the main ore zone in the AJ mine. Note the crosscutting geometry of the ore zones in relation to the regional fabric. Location of section A–A′ shown in Fig. 2.

pable unit of altered greenstone. The quartz veins dip more steeply to the northeast than both the rocks and the metamorphic fabrics. At the mine scale, the ore zone is 4.5 km long and up to 200 m wide and is slightly discordant (8–20°) to the regional fabric (S_2) in both strike and dip. The ore zone trends more northerly than both the fabric and lithologic contacts, such that, from north to south, it strikes into the greenstone–phyllite contact (Fig. 2). In the North orebody (NOB) the footwall of the ore zone occurs in the phyllite 120 m east of the greenstone–phyllite contact. In the South orebody (SOB) near the Perseverance mine the ore zone crosses the greenstone contact with some of the mineralization hosted in the greenstone.

Metamorphism

The lode deposits of the AJ mineral system occur in regionally metamorphosed rocks near the greenschist–amphibolite facies transition (Fig. 3). From southwest to northeast, the metamorphic assemblages exhibit a Barrovian metamorphic sequence ranging from lower greenschist to upper amphibolite grade (Forbes 1959; Himmelberg *et al.* 1991). Field mapping of isograds (Ford and Brew 1973) suggests that higher grade rocks systematically overlie lower grade rocks. One kilometre east of the AJ mine, metamorphic conditions reached a peak of at least 4.2 kbar (1 kbar = 100 MPa) and 500°C, based upon the stability of garnet + quartz + muscovite + chlorite + biotite (Himmelberg *et al.* 1984). Sphalerite geobarometry and arsenopyrite geothermometry data from the AJ deposit indicate pressures of 3–4 kbar and temperatures of >300°C (Newberry and Brew 1987).

Peak metamorphism and at least five metamorphic events occurred in the area prior to mineralization (Brew *et al.* 1989). Gehrels *et al.* (1991) have obtained an age of 71.6 ± 1.2 Ma from zircons in the Mount Juneau pluton which crosscuts the regionally metamorphosed sequence (Ford and Brew 1973). However, the Mount Juneau pluton is itself penetratively foliated, and garnet occurs locally within the intrusive (R. Newberry, personal communication, 1991). K–Ar dates on muscovite from auriferous veins in the AJ deposit which clearly crosscut the penetrative fabric yielded an age of 55.3 ± 2.1 Ma (Goldfarb *et al.* 1987). Although the absolute timing of mineralization with respect to metamorphism is enigmatic, the radiometric age of the veining, combined with the crosscutting geometry of the veins and the metamorphic fabric, are consistent with a mineralizing event subsequent to peak metamorphism of the immediate host rocks.

Structural geology of the AJ deposit

Folding

Four generations of folds have been identified in the study area. Folds of the earliest generation (F_1) are readily evident at the mesoscopic scale. F_1 folds are isoclinal, with axial surfaces folded about F_2 axes. F_1 folds are tight, with wavelengths up to 50 cm and amplitudes less than 1 m. The S_1 fabric is a schistosity defined by the alignment of phyllosilicates. S_1 is subparallel to F_1 axial surfaces on the limbs of folds.

F_2 folds fold the S_1 fabric. They are isoclinal, with northwest-striking and steeply northeast-dipping axial surfaces; fold axes plunge moderately southeast in the NOB and SOB (Fig. 4). The F_2 folds have amplitudes of 150–600 m and wavelengths

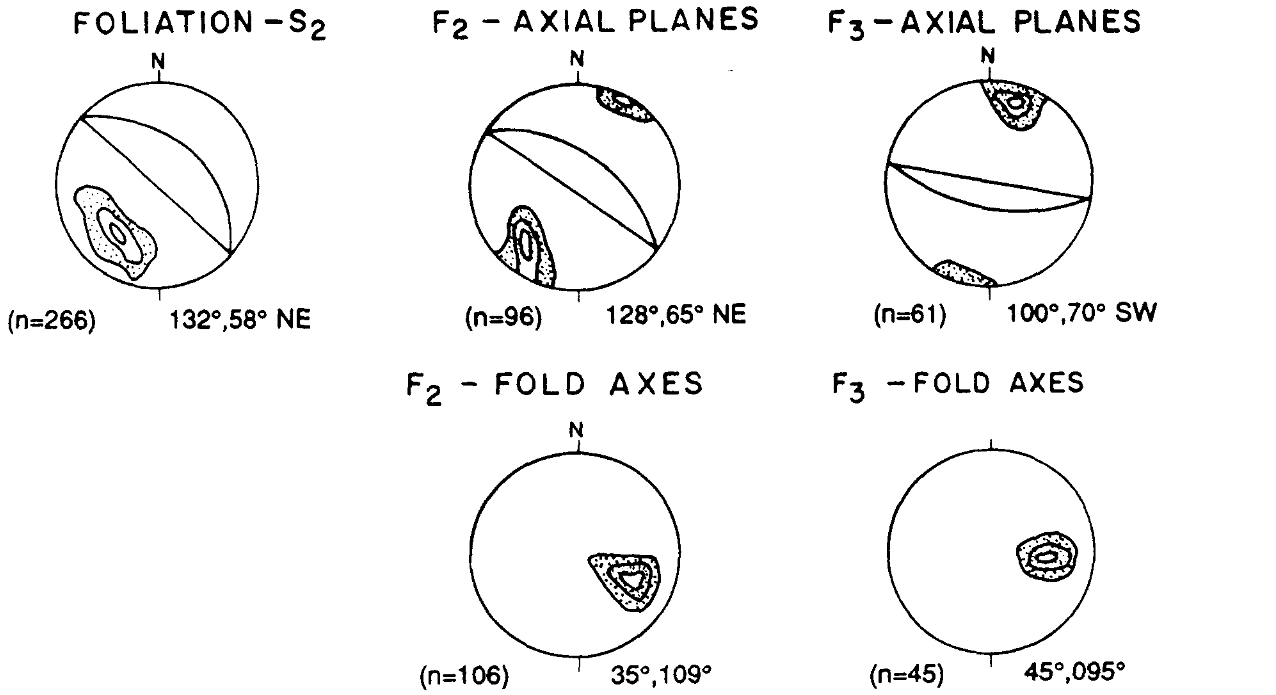

FIG. 4. Equal-area-net plots of F_2 and F_3 structures in the AJ mine (lower hemisphere projections). Contours indicate 1, 5, and 15 points per 1% area.

up to 450 m. One such southeast-plunging F_2 fold occurs in the Perseverance Slate where it folds both phyllite and metagabbro. This fold is referred to as the AJ synform. Along the strike of the deposit, from northwest to southeast, the attitude of F_2 fold axes changes from moderately north-northeast-plunging to southeast-plunging (Fig. 5).

F_3 folds were observed only in the felsic phyllites (Fig. 2). They have moderately southeast-plunging axes and steeply southwest-dipping axial surfaces (Fig. 4) which set them apart from F_1 and F_2 folds that have northeast-dipping axial surfaces. F_3 axial surfaces are perpendicular to the enveloping surfaces formed by the F_2(?) fabric. The F_3 folds are open, with interlimb angles between 100 and 130°. F_3 folds are symmetric and may be due to buckling of the felsic phyllite during northeast to southwest contraction.

Postmineralization (F_4) minor folds are defined by folded auriferous quartz veins. The folded veins are located near and within northwest-striking and northeast-dipping, ductile–brittle shear zones. The occurrence of folded auriferous quartz veins near and within shear zones indicates continued shear and folding after mineralization. Asymmetries of all the phases of folds can be attributed to a northeast-over-southwest sense of shear.

Planar fabrics

Five planar fabrics have been identified in the AJ mine area. The oldest is primary compositional layering (S_0), which is folded by F_1 folds. S_0 is generally parallel to S_1 except in the hinge areas of F_1 folds. S_1 is axial planar to F_1 folds and has been folded by F_2 folds.

S_2, the dominant fabric in the study area, is a penetrative foliation, defined by phyllosilicate minerals, which is axial planar to F_2 folds. In the hinge regions of F_2 folds, S_2 forms cleavage fans, and refraction is common between layers of contrasting lithology.

S_3 is a spaced crenulation cleavage that is oriented parallel to the axial planes of F_3 folds. The S_3 fabric is limited to the hinge regions of F_3 folds where it crosscuts S_2.

Fabrics interpreted as S–C mylonites were locally identified within discrete shear zones in the mine area. S-surface fabrics are referred to as S_2', and those interpreted as C-surfaces are referred to as S_2''. The S–C surfaces strike northwest and dip northeast. In thin section the S_2' fabric is defined by recrystallized quartz, feldspar, and mica grains. The crosscutting S_2'' fabric is defined by an anastomosing array of subparallel mica and opaque minerals. Asymmetric porphyroblasts of garnet, feldspar, quartz, and mica are present within S_2''. The S_2' and S_2'' fabrics are 15–20° apart. Kinematic interpretation of the geometry of these fabrics gives a northeast-to-southwest sense of shear.

Linear fabrics

Two intersection lineations are present. The first is formed by the intersection of the S_2 and S_1-S_0 fabric. The second intersection lineation is defined by the intersection of auriferous quartz veins with the S_2 fabric. Both lineation sets parallel the F_2 fold axes.

Other common lineations include quartz rods and mineral elongations. Mineral lineations are defined by aligned amphiboles which are dominantly oriented perpendicular to the F_2 fold axes within the plane of the S_2 foliation. A second orientation occurs where the amphiboles are aligned subparallel to the F_2 fold axes. Finally, boudins of auriferous quartz veins occur in three orientations. Two sets of boudin lines plunge moderately northwest and southeast, and a third set plunges steeply east-northeast.

Shear zones

Shear zones at the AJ mine crosscut the S_1, S_2, and S_3 fabrics and offset F_1, F_2, and F_3 folds, indicating that the latest movement postdates the regional folding events. The

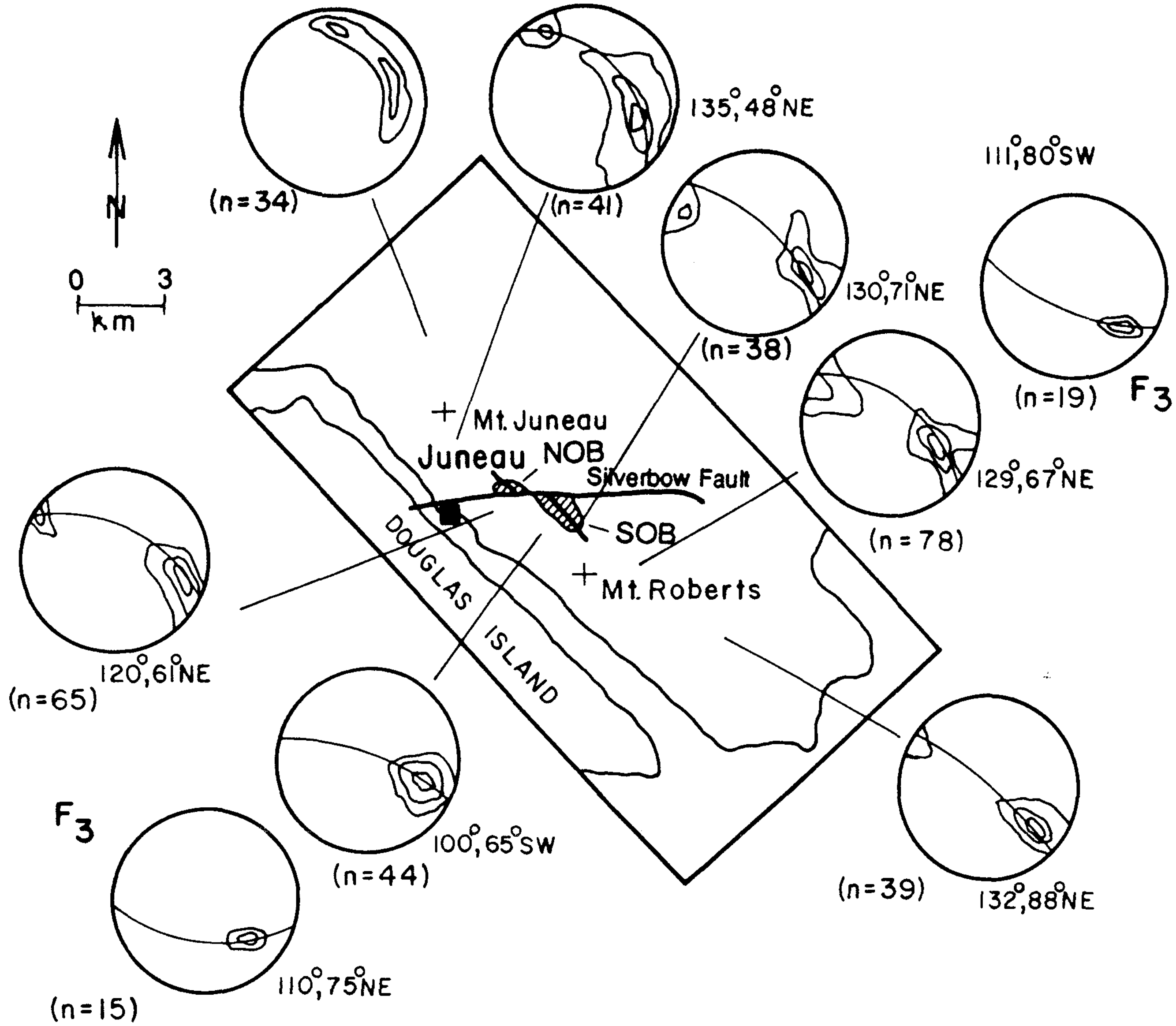

FIG. 5. Plan map with stereonets of fold axes in the AJ mine area, showing the change in fold axis plunge from northwest–southeast across the study area. All orientations are of F_2 folds except as noted. NOB, North orebody; SOB, South orebody.

shear zones range from brittle (cross shears) to ductile (strike shears) in character. Two dominant shear-zone orientations are present (Fig. 6). The more abundant strike shear zones are at a low angle to the general structural grain of the area, striking northwest and dipping moderately to steeply northeast. The subordinate cross shear zones strike east-northeast and dip steeply north or south.

Strike shear zones

The northwest-trending strike shear zones occur throughout the deposit. They do not form boundaries to the ore as much as they constitute zones (up to 200 m wide) that contain the auriferous veins. Strike shear zones are subparallel to both the strike and dip of the ore zone. The strike shear zones trend more northerly and dip more steeply than the lithologic contacts (Werneke 1932; Wayland 1939). In places the shear planes are undulatory, and zones of highly polished graphitic phyllonite or phyllite up to 1.2 m thick may be present. Strike shear zones contain auriferous quartz veins that have been transposed into the shear, folded (F_4) and boudinaged.

Based on the vergence of asymmetric porphyroblasts and S–C fabrics within and near the shear zones, reverse movement occurred along the strike shears prior to mineralization. Postmineralization normal movement can be documented along northwest-trending strike shear zones, based on sigmoidal schistosity, asymmetric quartz boudins, the vergence of shear folds, and offset quartz veins. Evidence for both normal and reverse displacement may occur within the same shear zone based on sigmoidal schistosity. Such a geometry is interpreted to be the result of a major component of flattening perpendicular to the shear zone. However, offset sigmoidal schistosity indicates that the most recent sense of displacement on most of the strike shear zones was oblique right-lateral reverse.

Although reverse shear occurred before mineralization, the extent to which the strike shear zones were active prior to mineralization is unknown. Folded auriferous veins indicate that ductile deformation continued after mineralization, and auriferous veins within shear zones cutting across shear-induced foliation suggest that at least some of the mineralization was synchronous with, or slightly later than, the earliest stages of faulting.

Cross shear zones

Cross shear zones strike east-northeast (065 – 090°) and dip steeply (80 – 90°) north and south. They offset lithologic contacts, the strike shear zones, and the mineralization. Graphitic gouge zones from a few centimetres to 1 m wide are characteristic of these shear zones. Slickensides on polished surfaces plunge moderately to the west. The most prominent shear zone of this type is the Silverbow fault, a 4 – 25 m wide zone that has 540 m of left-lateral, down-to-the-north displacement (Fig. 2) (Werneke 1932; Wayland 1939).

Chronology of structures

F_1, F_2, and F_3 fold events were followed by, or synchronous with, the development of the strike shear zones. Auriferous veining was synchronous(?) with movement along the strike shear zones and local extension. After mineralization there was continued movement along the strike shear zones resulting in the development of F_4 folds. These structures were in turn cut by postmineralization cross shear zones.

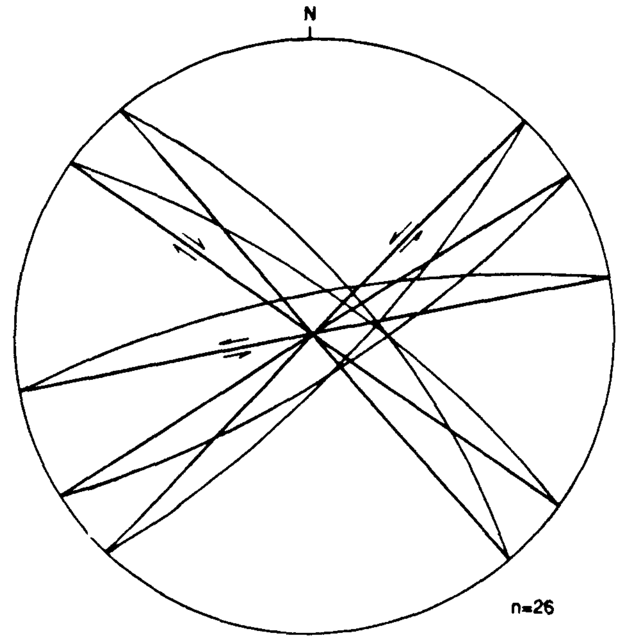

FIG. 6. Stereoplot of the principal shear orientations in the AJ mine (lower hemisphere projection).

Veins

The geometries of four mineralized vein sets (sets 3 – 6) in the AJ orebody can be attributed to a progressive mineralization event, with the veins emplaced during tensional brittle fracturing. Quartz veins of sets 1 and 2 are folded by F_2 folds and are interpreted to have been emplaced synchronously with progressive metamorphism. The economically important ore-bearing veins of sets 3 and 4 strike northwest and dip northeast and southwest. Although both of these vein sets occur in phyllite and metagabbro, their geometric relations are best exemplified in the competent metagabbro. Because the metagabbro bodies have been least affected by postmineralization deformation, the geometric relations of the auriferous veins are believed to most closely resemble their initial geometries. Two economically less significant vein sets (sets 5 and 6) strike east and northeast.

The majority of the northwest-striking veins dip moderately to steeply (60 – 75°) northeast (set 3). The other northwest-striking veins dip steeply (70 – 85°) southwest (set 4). These two vein sets are 35 – 44° apart (Fig. 7) and are not axial planar to any fold set. Individual veins of both sets range from 3 cm to 3 m in width (average 12 cm) and extend for tens of metres along strike and dip. The vein swarms occur in close proximity to northwest-striking and northeast-dipping strike shear zones.

Northeast-dipping veins (set 3)

Northwest-striking, northeast-dipping veins crosscut the S_0, S_1, S_2, and S_3 fabrics. These veins dip 8 – 15° more steeply and strike 5 – 10° more northerly than the foliation. Veins are boudinaged and locally folded near strike shear zones. The veins are lenticular and have sharp wall-rock contacts. Larger veins branch into smaller veins along foliation.

Boudinage is present in 75% of the veins studied. Where boudinage has strongly attenuated the veins, they are subparallel to the foliation, probably due to rotation into the flattening plane after vein emplacement. Veins in the phyllite have been subjected to greater strain, as indicated by folding and extensive boudinage, than veins in the metagabbros. However, boudinage is not uncommon in the veins hosted by the metagabbros.

The veins of set 3 locally display a sheeted or laminated structure caused by the inclusion of tabular sheets of the schistose wall rock in the vein. The wall rock inclusions are generally less than 0.2 cm wide and account for less than 5% of a vein by volume.

Southwest-dipping veins (set 4)

The southwest-dipping veins (set 4) are straight walled, do not have a well-developed laminated texture, and are more vertically continuous than set 3. They strike northwest and dip 70 – 80° southwest, cross foliation at a moderate angle (30 – 40°), and occur locally in en-echelon sets. Carbonate fibers are locally present in the veins and are oriented at 70 – 80° to the vein walls (Fig. 7). Veins of set 4 are found in all lithologies but are most abundant in the relatively competent metagabbro and greenstone.

Gently dipping and northeast-striking veins (sets 5 and 6)

Auriferous veins of set 5 strike easterly and dip gently (25 – 40°) northeast and southwest. This set constitutes less than 3% of all mineralized veins. These gently dipping veins are tabular and have sharp wall-rock contacts in the competent rocks (metagabbro and greenstone). Carbonate fibers in the veins are oriented perpendicular to the vein walls. These veins range in length from 0.6 to 1.8 m along strike and dip and average 45 mm in width.

Veins of set 6 strike northeast (045 – 075°) and dip subvertically northwest and southeast. They are variable in length (up to 4.5 m) and average 9 cm in width.

Relative-age relationships between vein sets

The relative age of emplacement of the auriferous veins of sets 3 – 5 is not clear. In 75% of approximately 50 cases studied, the northeast-dipping veins (set 3) are cut by the southwest-dipping veins (set 4). The gently dipping set (set 5) cuts across the northeast-dipping set (set 3), but in turn is locally cut by southwest-dipping veins (set 4). Vein sets 3 – 5, are interpreted to be roughly contemporaneous on the basis of

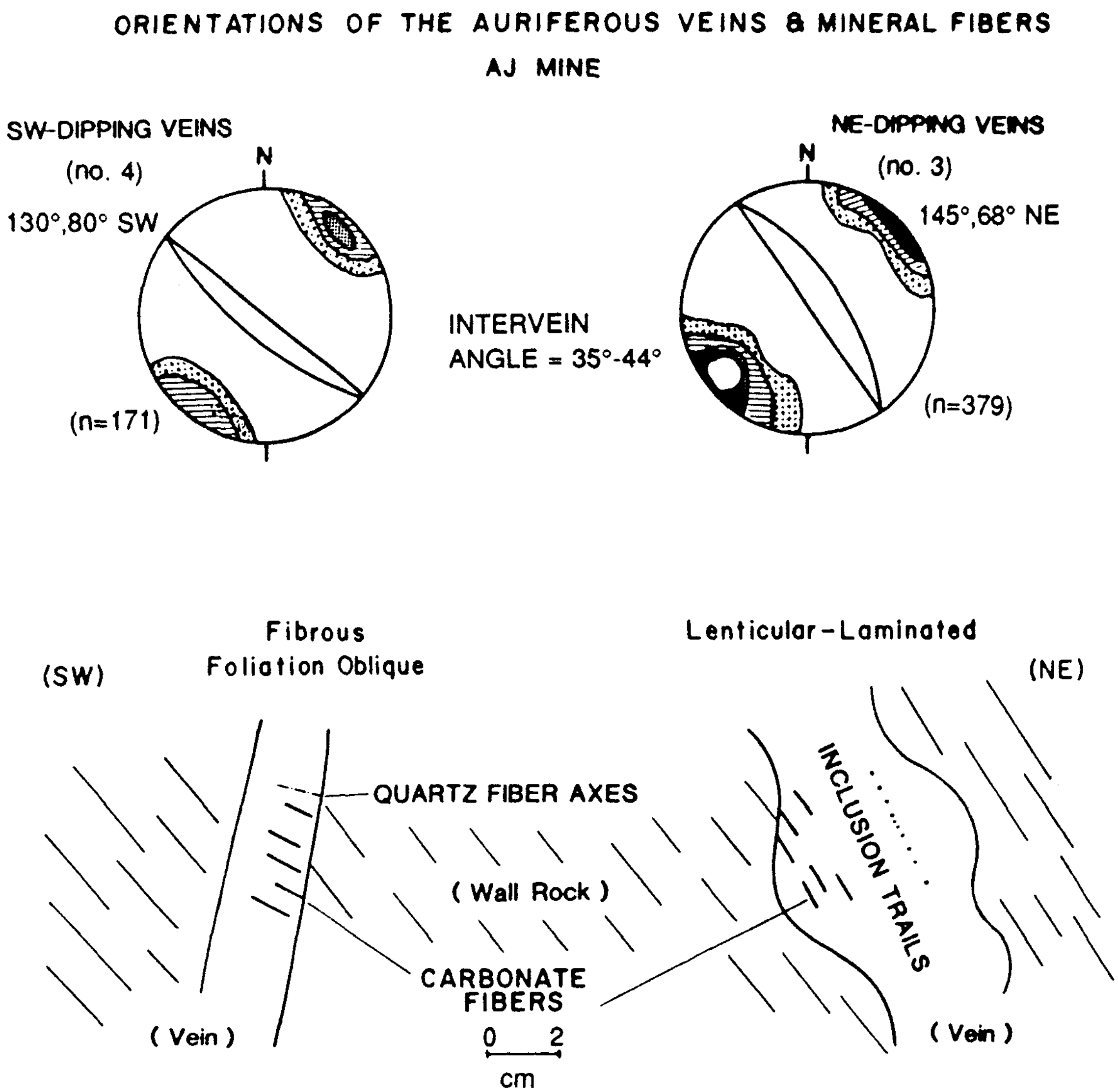

FIG. 7. Stereoplots of poles to planes and schematic sketch of sets 3 and 4 veins. Note the angular relations and the orientations of the mineral fibers. Contours indicate 1, 5, 15, and 25 points per 1% area.

their mutually crosscutting relationships (Fig. 8). The veins of set 6 cut all other sets and are therefore interpreted to have been the last to form.

Auriferous veins: internal textures and the strain ellipse

The orientation of carbonate and quartz fibers as well as inclusion trails within the auriferous veins of the AJ mine have been used to determine the kinematics of vein development. The importance of crystal fibers in tracking the incremental displacement history of veins and the sense of shear has been emphasized by various workers (Ramsay 1980; Cox and Etheridge 1983; Ramsay and Huber 1983). The postmineralization kinematics can be determined by interpretation of the geometries of boudinaged veins. Finally the geometry of the internal textures of the veins can be used to interpret the effects of fluids and deviatoric stress upon veining.

Fibers

Both northwest-striking vein sets contain carbonate fibers (Fig. 7). Carbonate fibers were found to be most abundant in the veins of set 4 (fibers occurred in 20% of the veins observed) and were significantly less abundant in the veins of set 3 (8% of the veins observed). Fibers in set 3 are oriented at a low angle (<40°) to the vein margins, whereas fibers in set 4 lie at 70−80° to the vein margin (Fig. 7). Both vein sets contain rare vugs indicative of open-space filling. Internal deformation of the veins is common, as indicated by deformed sulfide minerals and rotated carbonate fibers.

The mechanism and orientation of fiber growth depend on whether the vein formed by syntaxial growth or antitaxial growth. Syntaxial veins contain vein material of similar composition to the wall rock. In such cases the lattice orientation of the fibers in the veins may reflect that of the wall rock phases. Antitaxial veins differ in composition from the wall rock. In such cases, the long axes of the fibers parallel the bulk extension direction (Cox and Etheridge 1983). The veins in the AJ mine are clearly antitaxial. Based on theoretical considerations and empirical relationships observed in the AJ mine area, we believe that fiber orientations can be used to deduce the displacement of the vein walls. This contention, however, must be tempered by the results of Cox (1987) who demonstrated that the use of mineral fiber orientations alone to determine the

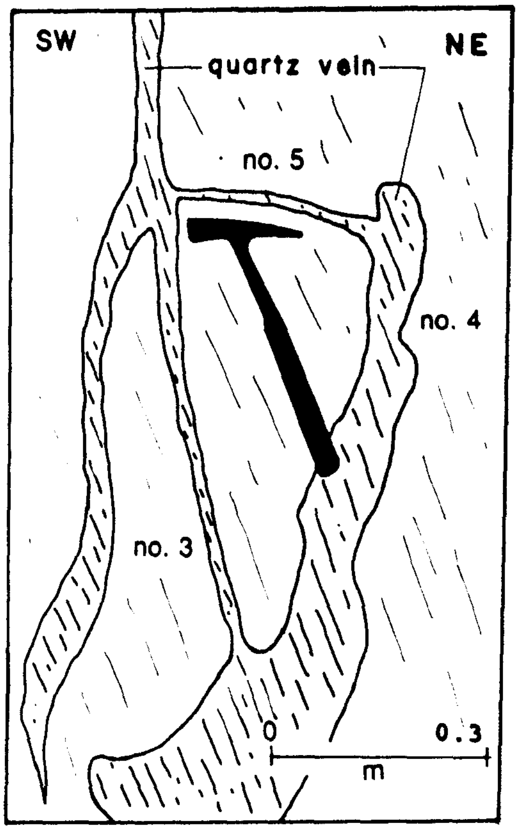

FIG. 8. Line drawing of the quartz veins of sets 3, 4, and 5; view southeast in cross section.

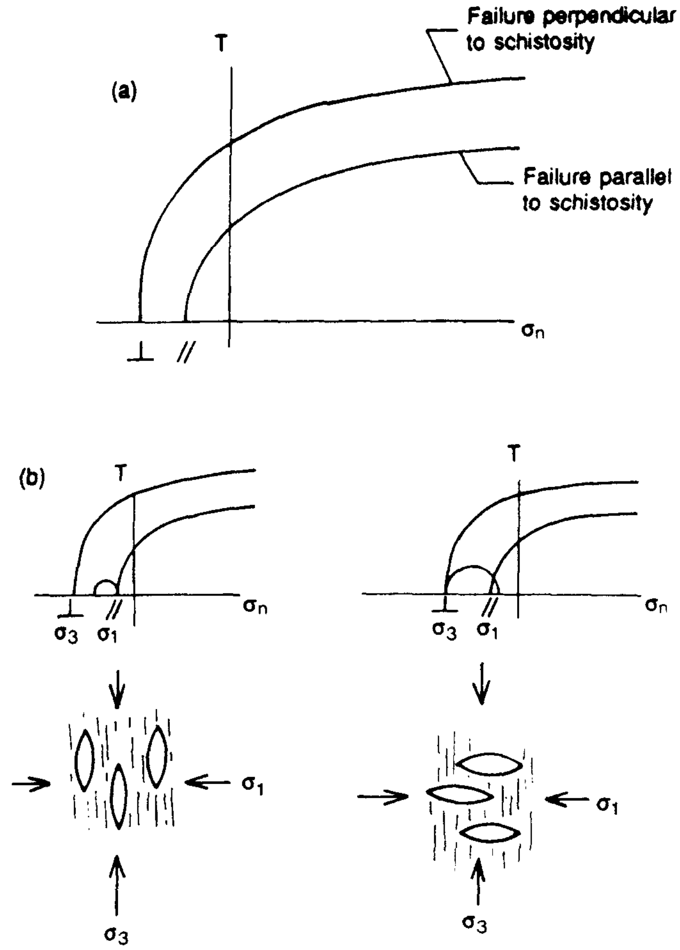

FIG. 9. (*a*) Mohr failure envelopes for failure normal to, and parallel with, schistosity. (*b*) Veining parallel to schistosity due to increased fluid pressure (p_f) under maximum compressive stress perpendicular to the fabric. (*c*) Veining perpendicular to schistosity under the same stress configuration with greater fluid pressure (from Kerrich 1986).

displacement history of a vein can lead to erroneous results. Inclusion trails and inclusion bands must be used in conjunction with the fibers to determine the correct kinematic history (Ramsay 1980).

Carbonate fibers and inclusion trails within the veins of sets 3 and 4 are parallel, suggesting that both veins opened in the direction of fiber growth. In the southwest-dipping veins (set 4), the carbonate fibers subtend 70–80° angles with the vein walls, indicating a strong extensional component during veining. In the northeast-dipping veins (set 3), the carbonate fibers subtend <40° angles with the vein walls, plunging more shallowly northeast, a relationship suggesting that the vein walls opened obliquely. A component of normal shear along some of the northeast-dipping veins during mineralization is implied. Based on the orientations of carbonate and quartz fibers in the southwest-dipping veins (set 4), we have determined that the *X*-axis of the strain ellipse plunges moderately (40–50°) east-northeast (070–085°), and the *Z*-axis plunges steeply southwest. These relations are interpreted to indicate that the northeast-dipping vein set (set 3) formed under conditions of normal shear and the southwest-dipping veins (set 4) formed as tension veins.

Boudinage

Postmineralization deformation is well documented by the boudinage of auriferous quartz veins. The veins pinch and swell alongstrike and alongdip, resulting in boudins with an elongate lensoidal "chocolate-tablet" shape (Barton and Light 1987). Throughout the mine, boudin axes generally plunge subhorizontally to shallowly northwest or southeast. The most common boudin set in the AJ deposit plunges moderately northwest (325–340°) in the plane of the vein. Based on the geometry of the boudins as well as elongation lineations of quartz on the vein surfaces, this northwest plunge is interpreted to correspond to the *Y*-axis of the finite strain ellipsoid. A second set of boudin axes plunges moderately (15–35°) to the east-southeast (100–115°), subparallel to the F_2 fold axes. A third, poorly developed boudin set plunges steeply east-northeast and was only observed in the SOB and Perseverance mines.

The geometries of the quartz vein boudins demonstrate that the *X–Y* plane of the finite strain ellipsoid is subparallel to the regional S_2 fabric, which formed after mineralization. The *X*-axis is oriented downdip.

Fluids and veining

The synchronous development of the veins of sets 3 and 4 in shear and tension requires a mechanism whereby the local state of stress changes. The laminated texture and sheeted morphology of the northeast-dipping veins indicate a crack–seal mechanism for vein formation (Ramsay 1980). The parallel bands or "trains" of opaque inclusions are interpreted to be due to successive episodes of hydrofracturing (Ramsay 1980).

Sphalerite geobarometric data indicate that the AJ mineralization took place under pressures greater than 3.5 kbar (Newberry and Brew 1987). Thus, to develop fractures at the depths postulated for the AJ deposit, veining must have been facilitated by hydraulic fracturing. Yardley (1983) states that the styles of fractures that develop will depend upon the magnitude of the deviatoric stress. He has described a situation similar to that at the AJ mine, in which syndeformational shear veins (Connemara Schists, Ireland) cut the regional fabric and are boudinaged where they are parallel to the foliation. Late-deformational veins that are extensional in origin opened perpendicular to the dominant elongation.

Mohr circle analysis

A Mohr circle analysis was used to determine the relationship between the lenticular–laminated veins (set 3) and the foliation-oblique veins (set 4). The key factors controlling vein formation are fluid pressure and deviatoric stress (Yardley 1983). Figure 9 shows a shear versus normal stress graph with Mohr failure envelopes for failure normal and parallel to schistosity. Kerrich (1986) suggests that veins can form parallel to the schistosity when the maximum principal stress is at a high angle to the fabric, provided that the fluid pressure exceeds the greatest principal effective stress (external stress). At the point where the fluid pressure exceeds the external stress, such that the Mohr circle moves to the left (Fig. 9*b*), tensile failure occurs.

Veins that crosscut the fabric may form in the same overall stress configuration as veins subparallel to the fabric if the fluid pressure increases further and intersects the envelope for failure perpendicular to schistosity (Fig. 9*c*). Based on this analysis, Kerrich (1986) concludes that extensional veins that crosscut the foliation reflect the greatest buildup of fluid pressure. Such an increase in fluid pressure could be episodic and may explain the differently oriented, yet mutually crosscutting veins at the AJ mine. Fluid-inclusion studies of quartz from the AJ deposit indicate episodic fluid immiscibility, indicative of such widely fluctuating fluid pressures (Goldfarb 1989).

Structural controls on mineralization at the AJ deposit

Previous structural models for the AJ deposit have ascribed the formation and control of the auriferous veins to axial planar fracture (Herreid 1962; Brew and Ford 1974) and to hydraulic fracturing (Barton and Light 1987). Both models were based upon a single northwest-striking vein set. Data from this study reveal that there are two main auriferous vein sets and two minor sets that are mineralized but do not constitute ore. The veins are not axial planar to any fold set (Fig. 3), and all of the auriferous vein sets crosscut the regional fabrics (i.e., S_0/S_1, S_2, and S_3). Interpretation of the data from this study suggests that the premineralization sense of shear was reverse based upon fabric asymmetries. Auriferous quartz veining at the AJ deposit accompanied a period of extension with down-to-the-northeast shear, followed by oblique reverse right-lateral shear.

Vein, fabric, and fold geometries

The two different orientations of the major vein sets (sets 3 and 4) suggest they may comprise a conjugate set whose dihedral angle was modified by syn- or postmineralization, noncoaxial deformation. The problem with such a model is that conjugate vein sets are best developed in a homogenous rock mass. This is clearly not the case for the AJ deposit where the structural fabric provides a well-defined anisotropy, and the interlayered phyllite and metagabbro provide a competency contrast. A conjugate set of veins should be symmetrically oriented about the stress axes; this study, however, suggests that the veins of sets 3 and 4 are not conjugate in any of the rock types at the AJ deposit. Lastly, a well-developed set of northwest-striking conjugate shears is also lacking in the AJ deposit, further exemplifying the strong structural control of the northeast-dipping fabric. Based on the embryonic understanding of vein systems in rocks with a strong anisotropy, it would be erroneous to apply the mechanics of deformation of homogenous rock to vein control at the AJ deposit.

An important control on mineralization is the regional (S_2) fabric and the strong anisotropy provided by the interlayered phyllite and metagabbro units. The alternating layers of phyllite and metagabbro are in part the result of tight to isoclinal infolding within the southeast-plunging F_2 AJ synform. Fracturing during extension was facilitated by the competency contrasts between the metagabbro and phyllite. To some extent vein orientation is dependent on rock type. Dramatically different attitudes and geometries of the veins can be observed between the competent metagabbro and the less competent phyllite.

The plunge orientations of F_2 fold axes change from northwest to southeast across the deposit. The apex of the change from northerly plunges to southerly plunges coincides with the location of the North and South orebodies of the AJ mine (Fig. 5).

Geometry of the ore zone

The ore zone in the SOB, defined by vein swarms, plunges moderately southeast. We interpret this plunge as due to the intersection of the southeast-plunging AJ synform and the northeast-dipping strike shear zones. The NOB mineralization has a similar plunge to that of the SOB. The widest ore zones (up to 200 m) occur in the NOB where infolded metagabbro and phyllite are crosscut by several northwest-striking and northeast-dipping shears that have had oblique-normal and reverse movement. Narrower ore zones (15–30 m) are present adjacent to shears that transect homogenous metagabbro and greenstone, such as the Nugget Gulch fault in the SOB.

The crosscutting relationship of the veins to the S_1/S_0, S_2, and S_3 metamorphic fabrics is evidence that fracturing occurred at a slight angle to the regional fabrics and followed the early ductile events that produced those fabrics. However, the auriferous veins at the AJ mine are interpreted to have been emplaced during continued ductile deformation, as supported by the folded and boudinaged veins. The formation of the veins of sets 3 and 4 in parallel swarms, the deformed geometry of the veins, and their crosscutting relationship to the regional fabric are compatible with the hypothesis that the veins formed as shear and tensile fractures in a northwest-striking and northeast-dipping shear zone during down-to-the-northeast shear.

Discussion

The main period of mineralization (vein sets 3 and 4) occurred during regional ductile deformation with local brittle failure of the host lithologies. The AJ deposit formed under "mesothermal" (i.e., moderate *P* and *T*) conditions within a dominantly reverse shear zone that experienced extension during vein development. The interpretation of the structural relationships of all ore-bearing vein sets (sets 3–6) supports a model of an evolving system in which veining began under

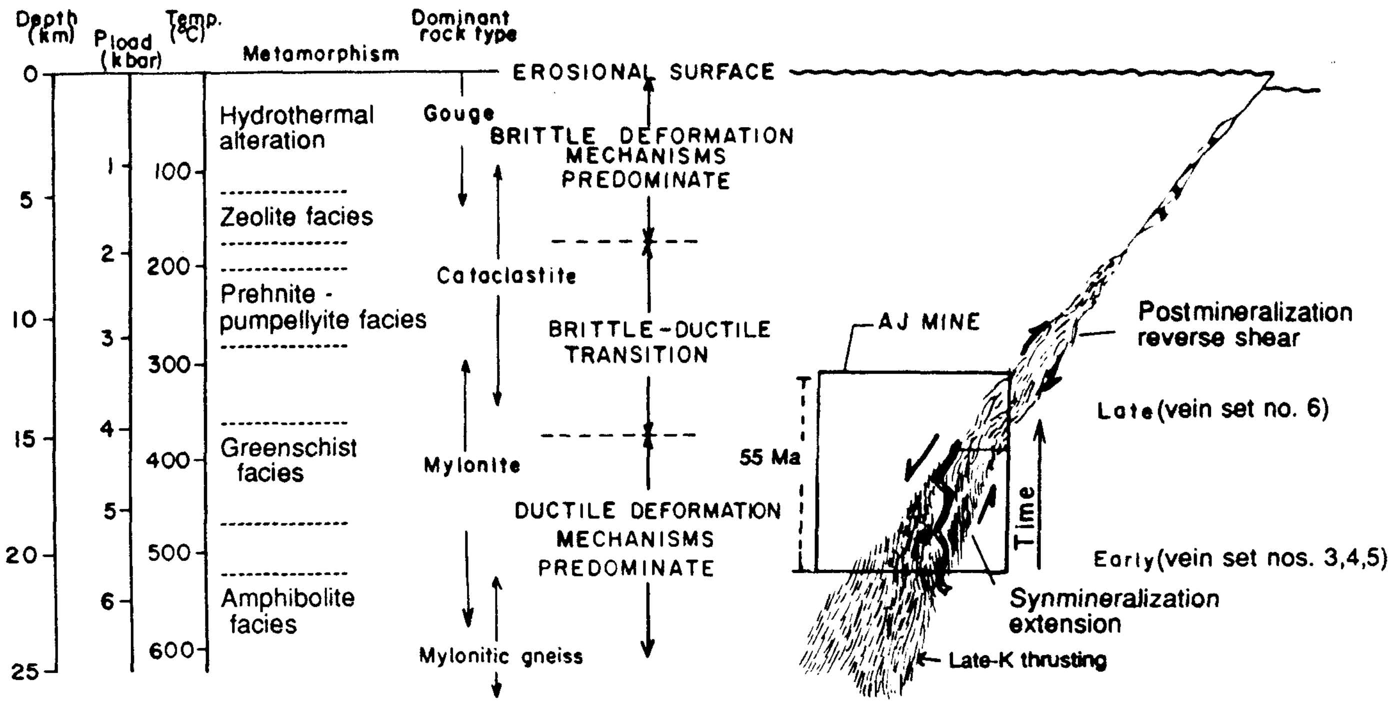

FIG. 10. Pressure and temperature regimes and the corresponding shear fractures controlling vein geometries. Note the inferred progression of veining at the AJ deposit (after Sibson 1977, 1983; Colvine *et al.* 1988).

ductile conditions and continued into the brittle regime. Evidence of ductile deformation is ubiquitous throughout the deposit and is indicated by the pervasive foliation, as well as by folded and boudinaged auriferous quartz veins. The strong anisotropy may have controlled the orientation of the northeast-dipping shears that lack a well-defined conjugate set. Finally, the geometric relationships between the northwest-striking, right-lateral strike shears and the east-northeast-striking, left-lateral cross shears are similar to the geometries that would be expected in a transpressive shear zone (Tchalenko 1970; Hancock 1985). The extension and subsequent fluid release may be related to a rotation of the stress configuration due to a change in Pacific – North American plate interactions from dominantly compressive to transpressive between 56 and 43 Ma (Engebretson *et al.* 1985).

The ductile deformation and the structural relationships of the veins, sulfide geobarometry and geothermometry (Newberry and Brew 1987), and fluid-inclusion studies (Goldfarb *et al.* 1987) all indicate that the AJ deposit formed at mesothermal levels. Figure 10 is a schematic representation of the inferred geometry of the vein systems that formed along shear fractures at the AJ mine over a range of pressure and temperature conditions. As indicated in Fig. 10, the types of structures in the AJ deposit are compatible with a depth of emplacement of 10–15 km (3–4 kbar). The mineralized vein sets, which show evidence of both ductile (sets 3–5) and brittle (set 6) deformation, indicate that the hydrothermal system existed over a range of structural conditions.

Conclusion

Regional studies near Juneau (Gehrels *et al.* 1990), in the Holkham Bay area (Stowell 1987; Stowell and Hooper 1990), and in the area south to Prince Rupert (Crawford *et al.* 1987, 1989; Rubin *et al.* 1990) have demonstrated that southwest-directed thrusting occurred along the western side of the Coast Mountains during mid-Cretaceous time. Evidence for Late Cretaceous to Paleocene extension in the region, with west-side-up displacement along northeast-dipping or near-vertical shear zones, has been documented south of Juneau (McClelland *et al.* 1990; Gehrels *et al.* 1992) and near Prince Rupert along the Work Channel Lineament (Crawford *et al.* 1989). The structural relations of the veins to fabrics at the AJ deposit, as well as the isotopic dates of mineralization (Goldfarb *et al.* 1987), suggest that veining closely followed the extension events that have been documented to the south.

Based on the pre-, syn-, and postmineralization kinematic indicators, the structural evolution of the AJ deposit is interpreted as follows:

(1) F_1 and F_2 isoclinal folds and F_3 upright folds developed during a progressive contractional deformational event (mid-Cretaceous to Tertiary deformation). The dominant fold event in the mine area, F_2, is exemplified by the AJ synform depicted in Fig. 11*a*. A northeast-over-southwest sense of shear in ductile shear zones (Fig. 11*a*) was synchronous with the fold events in the AJ area. Northeast-over-southwest shear during the early ductile events is also documented south of Juneau by Stowell (1987) and Stowell and Hooper (1990).

(2) Mineralization postdating metamorphism of the immediate host rocks occurred at approximately 55 Ma (Goldfarb *et al.* 1987; Newberry and Brew 1987; R. J. Goldfarb, personal communication, 1990). Two sets of northwest-striking auriferous veins were emplaced during a period of extension within the shear zones and near the contacts between rocks with high competency contrasts (Fig. 11*b*). The extensional event is evidenced by normal shear along some of the northeast-dipping veins and carbonate fibers in the veins of sets 3 and 4.

(3) Postmineralization, reverse right-lateral shear occurred, as indicated by the offset of auriferous veins of set 3.

(4) The shift from a dominantly contractional to a transpressive deformational regime occurred after the mineralizing event and resulted in the development of cross faults with left-

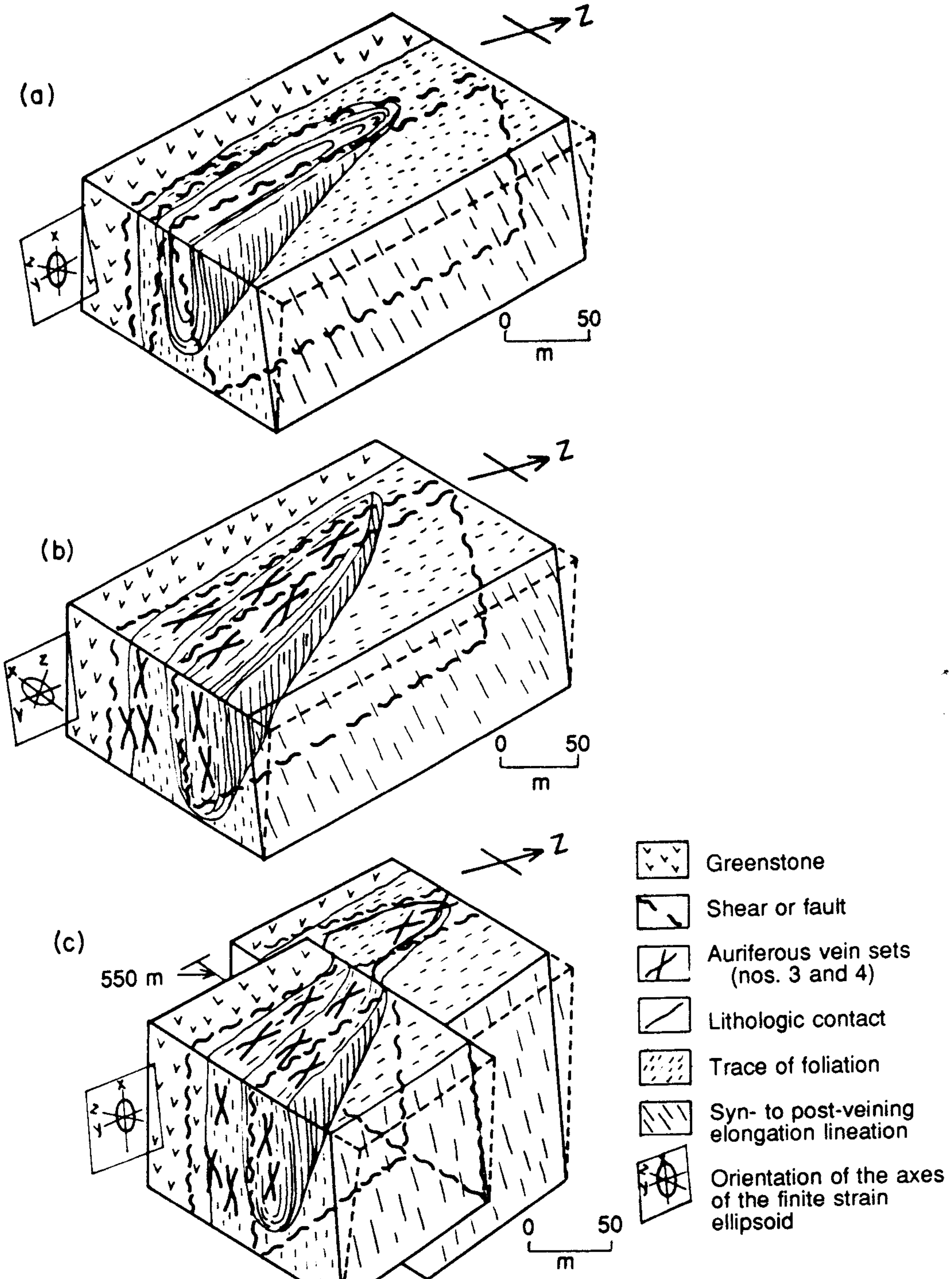

FIG. 11. Block diagrams showing the structural evolution of the AJ deposit. (*a*) Development of ductile shear zones. (*b*) Auriferous veining within the shear zone and in areas of infolded metagabbro and phyllite. (*c*) Postmineralization brittle deformation with left-lateral offset of the orebody along the Silverbow fault.

lateral movement, such as the Silverbow fault (Fig. 11*c*). Movement along the northwest-striking structures was reverse right-lateral (Stowell and Hooper 1990; this study).

Structural evidence from this study (shear, vein, and fiber orientations) supports the hypothesis that the auriferous quartz veins are related to the structural evolution of a shear zone that experienced local, and possibly regional, extension. Localization of veining within the deposit was controlled by folds in metagabbro and phyllite which plunge southeastward along the F_2 AJ synform. The competency contrasts of these rocks enhanced fracturing. The premineralization, reverse to reverse right-lateral sense of displacement in the shear zone may have facilitated subvertical fluid flow (Robert and Brown 1986; Sibson *et al.* 1988). Preexisting shear zones, a change in fold and fabric orientation, and the infolded metagabbro and phyllite all may have helped to focus fluid flow.

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