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# Metre-scale band structures and associated veins in Archean metavolcanics: Aubelle gold mine, central Canada*

GHISLAIN TOURIGNY† and W. M. SCHWERDTNER

Department of Geology, University of Toronto, Toronto, Ontario, Canada M5S 3B1

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**Abstract**—Many large outcrops of deformed Archean metavolcanics display a plethora of small-scale structures. Detailed study shows that much of the structural complexity is caused by heterogeneous deformation and associated shear-sense reversals on individual material surfaces. This situation contrasts with ideal band models in which such shear-sense reversals simplify rather than complicate the final structural pattern.

Two generations of E–W band structures occur in schistose metavolcanics at the Aubelle Mine. The first structures are short limbs of Z-shaped buckle folds and akin to dextral kink bands, the second structures resemble sinistral shear bands but contain relics of Z-shaped folds. The emplacement and deformation of three sets of subvertical veins (V1, V2, V3) is compatible with the band-structure development and associated local reversal of shear sense in the horizontal plane. V1 and V3 are oblique to all other structures, but V2 is parallel to the band boundaries and is boudinaged in many places. The dilatant V2 was emplaced while the axis of instantaneous bulk shortening was within 45° of the dextral bands. Oblique deformation of the dextral bands led to boudinage of V2 and ultimately to extension fracturing of metavolcanics and emplacement of V3.

## INTRODUCTION

IN THE past decade, many structural geologists have analysed the deformation of schistose metavolcanics containing lode-gold deposits (Andrews *et al.* 1986, Robert & Brown 1987, Sibson *et al.* 1988, Dubé *et al.* 1989, Hodgson 1989, Sibson 1989). Such metavolcanics display assemblages of small-scale structures that have puzzled many workers. As suggested by Kerrich & Allison (1978) and reiterated herein, much of the apparent complexity may have been generated by reversals in shear sense.

Non-coaxial deformations such as general heterogeneous strain, homogeneous simple shearing, or the superposition of finite pure shears, can lead to sudden reversals in the sense of instantaneous tangential shear on rotating material surfaces. In an ideal zone of homogeneous sinistral simple shearing, for example, the instantaneous shear strain parallel to a fold-enveloping surface changes its sense (from sinistral to dextral) as the envelope trace rotates counter-clockwise past the principal axis of instantaneous shortening. Because of this shear-sense reversal, open S folds in passive markers may gradually be converted into tight Z folds (Ramsay *et al.* 1983, fig. 4).

Like trains of S folds, band structures (Paterson & Weiss 1966, Cobbold 1977) rotate during progressive deformation and thus the sense of instantaneous boundary-parallel shear may change (Dennis & Secor 1987, Williams & Price 1990). Such a change can cause a reduction in band width (Cobbold & Gapais 1986, mode 2 motion) that may be difficult to detect in the final geometric state. We have studied horizontal outcrops of schistose Archean metavolcanics in which the band-width reduction process appears to have been inhibited by dilational veins. This led to the development of two coplanar sets of (1) dextral contraction bands, and (2) sinistral extension bands (Ramsay & Huber 1987, p. 427).

## BELLETERRE GREENSTONE BELT

Located 10–25 km north of the Grenville Front (Rivers *et al.* 1989), the Belleterre greenstone belt (Fig. 1) contains a typical assemblage of metavolcanics,

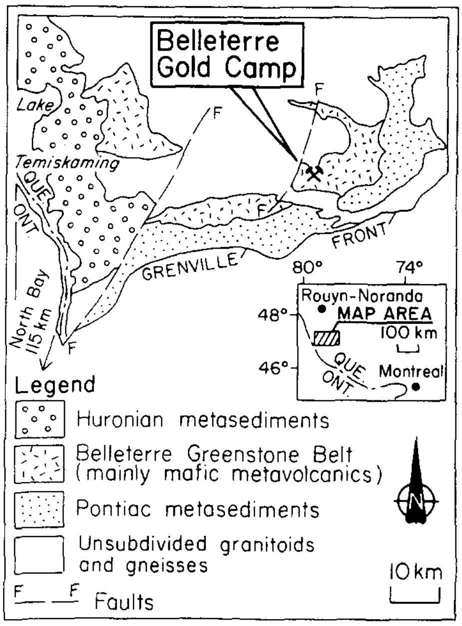

Fig. 1. Simplified geologic map of the Belleterre greenstone belt and location of the Belleterre gold camp.

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*Contribution A9032, Mineral Exploration Research Institute (IREM-MERI), Montreal, Canada.

†Present address: Ministère de l'Energie et des Ressources du Québec, Service Géologique du Nord-Ouest, 400 Boul. Lamaque, Val-d'Or, Québec, Canada J9P 3L4.

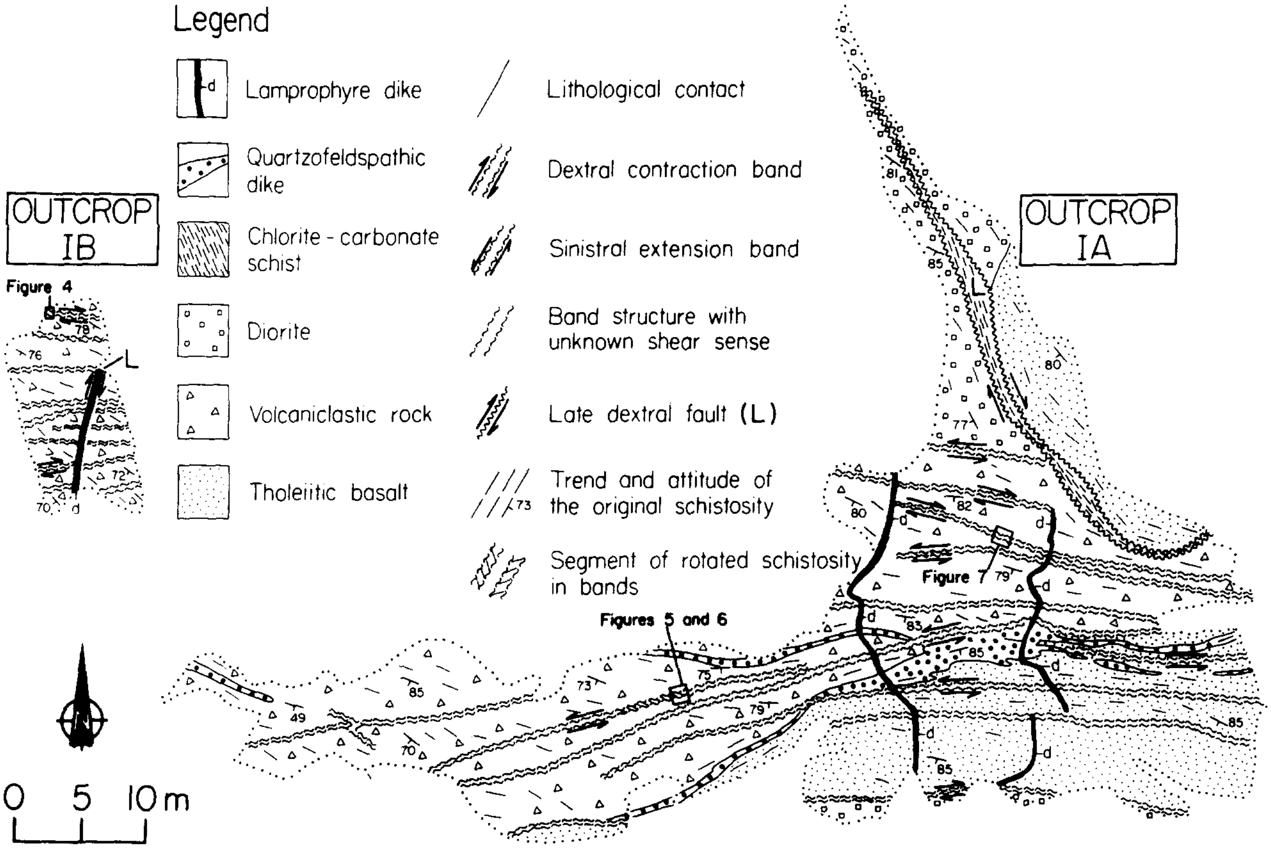

Fig. 2. Detailed geologic map of the Aubelle Mine outcrop. Insets show the locations of Figs. 4–7.

metasediments and metamorphosed diorite–gabbro. Archean metasediments of the Pontiac Group underlie the area between the Grenville Front and the Belleterre greenstone belt (Chagnon 1968, Imreh 1978), whose rocks are overlain unconformably by Proterozoic sediments.

Several greenstone outcrops were mapped by the first author on the scales of 50:1 and 100:1 using a plane table (Fig. 2). Most outcrops are stripped of soil and represent exceptional flat exposures at the site of former gold mines or gold prospects. Many outcrops exhibit several contacts between different supracrustal and metaplutonic rocks, so that structural relationships observable on the scale of metres or tens of metres may be geometrically similar to those on the scale of kilometres, at which lithologic boundaries are commonly mapped.

Ductile shear zones, which resemble those figured by Ramsay & Graham (1970), occur on the metre scale within sills of metadiorite and metagabbro that otherwise have isotropic mineral shape fabrics. Most of these sills have not been strained pervasively, but the sense of the E–W shear component is generally dextral.

*Schistose* metavolcanics contain spaced multimember Z folds, whose short limbs are here regarded as dextral contraction bands (Figs. 3 and 4). Narrow phyllonite zones are imposed concordantly on a number of these folds as well as on their schistose host rocks (Figs. 3, 5 and 6). The sense of horizontal shear is equivocal along most E–W phyllonite zones, but a few sinistral and dextral examples have been found within the host rocks (Fig. 3). We therefore reject the hypothesis that the Z folds formed by selective *sinistral* shearing of chevron structures (Cobbold & Gapais 1986, fig. 3, mode 2 with sinistral sense). Had this occurred hinge planes of Z-shaped relics of ideal chevron folds would bisect the interlimb angle, but this is not found in the present structure (lower-left quadrant of Fig. 4). Moreover, the sinistral shear scenario fails to explain why parasitic

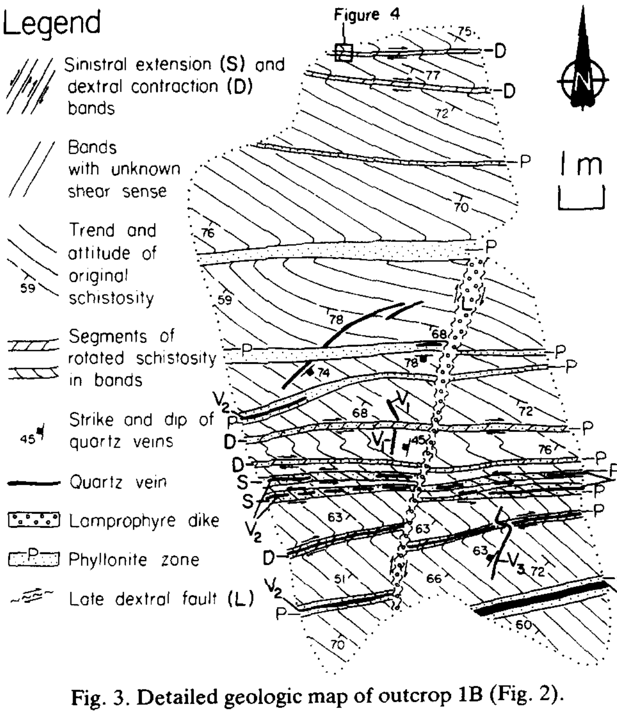

Fig. 3. Detailed geologic map of outcrop 1B (Fig. 2).

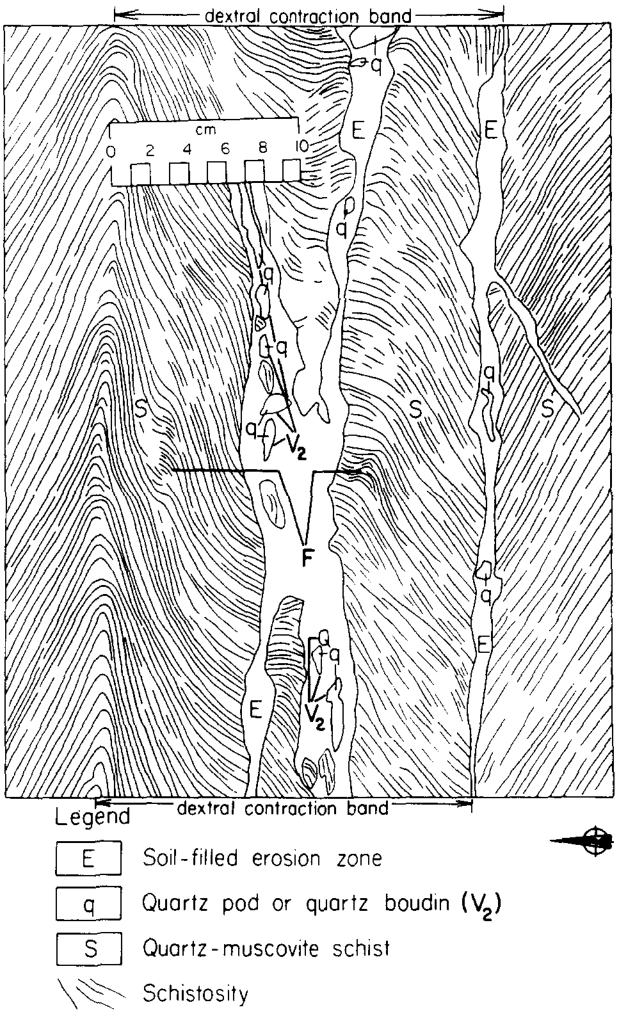

Fig. 4. Dextral contraction band at outcrop 1B (Fig. 3), drawn from an enlarged photograph. Note décollements adjacent to parasitic buckles (F) and their non-similar style.

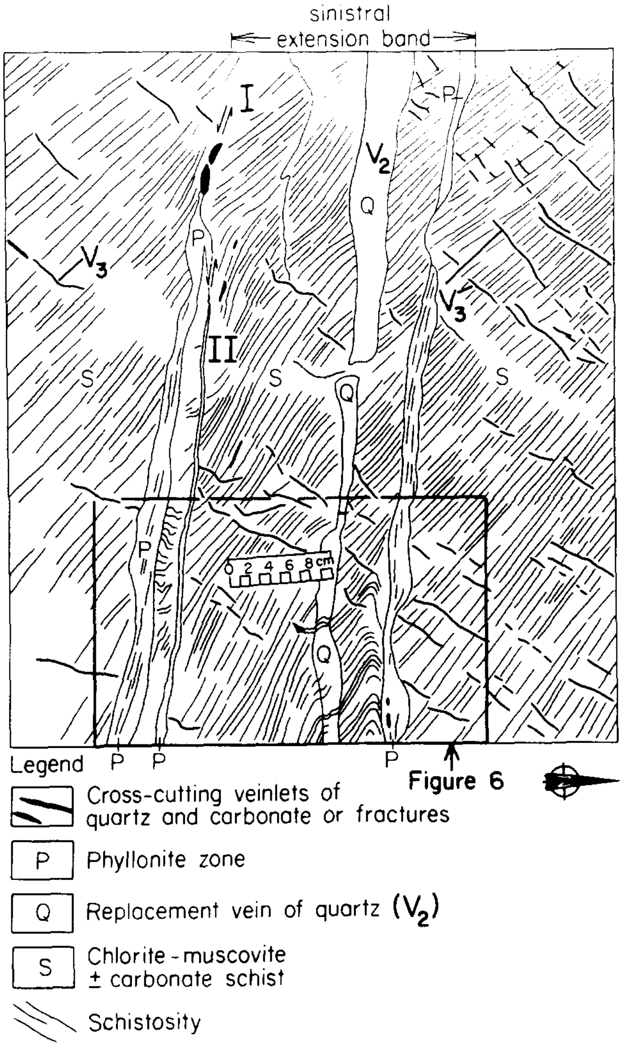

Fig. 5. Sinistral extension band containing a replacement vein of quartz and relict Z folds (drawn from an enlarged photograph). Note bending of the schistosity at the west end of the phyllonite zones (I, II). The inset shows the location of Fig. 6.

buckles are confined to the short limbs of the Z folds (F in Fig. 4).

## LARGE OUTCROP AT AUBELLE MINE

This outcrop (labelled #1) is located about 10 km north of the Grenville Front (Fig. 1), and consists of parts A and B separated by a strip of soil and shrubs (Fig. 2). The outcrop is dominated by metamorphosed mafic metavolcanic and felsic volcanoclastic rocks, which contain weakly deformed sills of metadiorite. These greenschist-facies rocks are cut by slightly deformed lamprophyre dykes and quartzo-feldspathic dykes. Most lithologic contacts and structural elements have steep attitudes, but the mineral grain lineation is subhorizontal throughout the outcrop. Schistosity trends approximately WNW–ESE, but its strike varies greatly with position (Figs. 2–7).

The latest dislocations are N-striking dextral faults, which cut all other band structures (L in Figs. 2 and 3). The tectonic relationship between these faults and the E–W sinistral extension bands (S in Figs. 3, 5 and 6) is uncertain. As the band structures are cut by the late faults at all localities and without exception, we reject

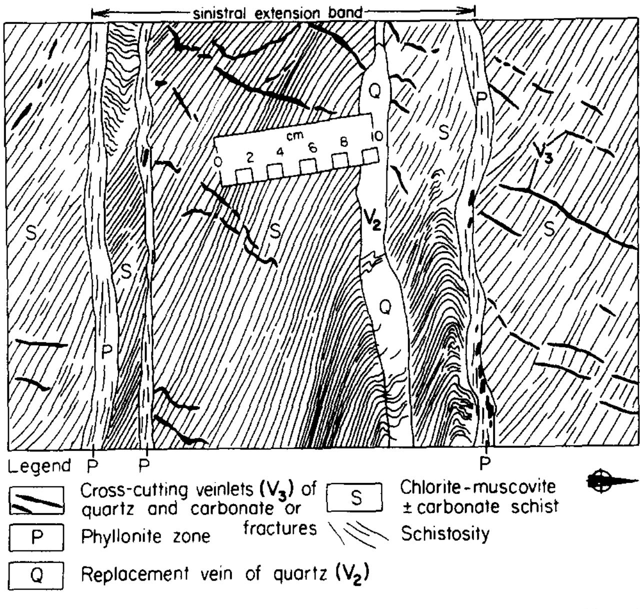

Fig. 6. Enlarged part of Fig. 5. Z-shaped folds are well preserved in this sinistral extension band (drawn from an enlarged photograph).

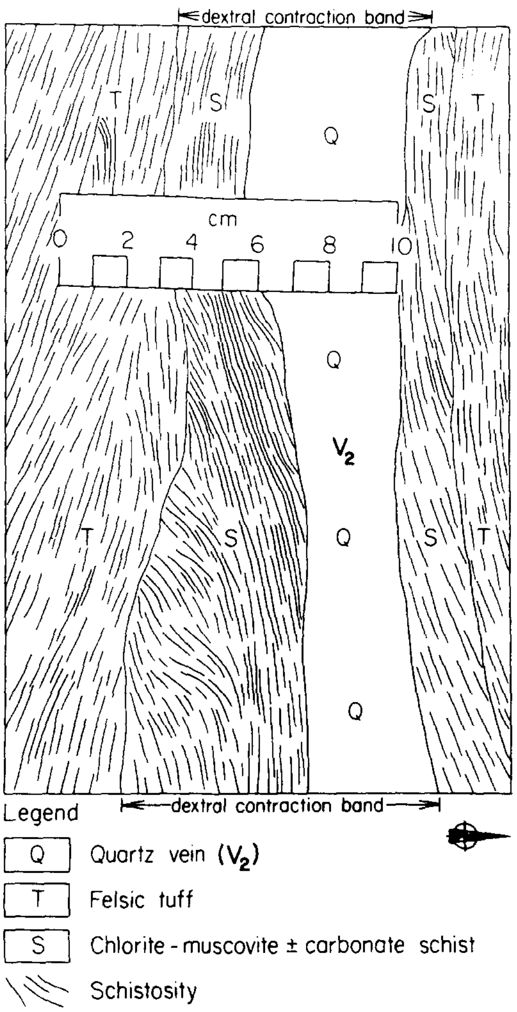

Fig. 7. Dextral contractional band with shear zone affinity (drawn from an enlarged photograph).

the possibility that bands and faults formed penecontemporaneously, in a late pulse of NE–SW bulk shortening.

Metre-scale dextral contraction bands are short limbs of Z folds (Fig. 4), ductile shear zones composed of chlorite–muscovite schist (Fig. 7), or phyllonite zones with concordant schistosity. Some phyllonite zones have oblique internal schistosity suggesting that they represent an intermediate structural stage between ductile shear zones and phyllonite zones with concordant schistosity. Unfortunately, we do not know to what extent the schistosity in the ductile shear zones (Fig. 7) is inherited from the schistosity of the metavolcanics. We therefore cannot discern whether the shear zones are derived from Z folds and how they actually developed.

The phyllonite contains >50% mica, with a grain size between 0.5 and 0.05 mm. Chlorite–muscovite–carbonate schist, on the other hand, is an alternation of quartz-rich layers and mica-rich laminae, and generally derived from felsic metavolcanics (Fig. 7). No detailed study was made of the grain fabric in thin section.

The sinistral extension bands are characterized by slight counter-clockwise rotation of the schistosity, and many of them are composite. Figure 5 shows such a structure containing boundary-parallel quartz veins and relict Z folds. The band boundaries coincide with irregular phyllonite zones, which seem to have been active at a late stage of the sinistral shearing. The west end of the southern boundary zone is marked by two vein pods (I in Fig. 5) and reveals the sense of differential displacement. Owing to the termination of the phyllonite zone, its sinistral shear had to be dissipated over a broader area (Schwerdtner 1973). This evidently led to slight bending of the schistosity of the wall rocks (on the south side). The same shear sense is apparent at the west end of the thin phyllonite band situated just north of the southern boundary zone (II in Fig. 5). The preservation of subtle flexures in schistosity of the wall rocks suggests that the sinistral shear is later than the dextral shear. Had band structures been created by an early sinistral shear, then a subsequent dextral shear would have reactivated and perhaps even propagated along the weak phyllonite zones, thereby destroying any flexures with sinistral shear sense.

No end regions are exposed of the dextral phyllonite zones (Fig. 3), at which a superimposed sinistral increment should be discernible. Because the sinistral E–W shear seems to have been small, at most localities, the dextrally oriented foliation within shear zones was not reoriented markedly. This also explains the preservation of close Z-shaped buckles in sinistral extension bands (Figs. 5 and 6).

Z folds are multilayered buckles as revealed by their near-parallel style and structural disharmony. Parasitic S-shaped buckles (F, Fig. 4) occur on the short limbs of well-exposed Z folds, and attest to the local sinistral shear parallel to schistosity—a requirement for buckling as well as kinking. The development of parasitic buckles and band structures leads to local perturbation of the instantaneous bulk deformation. This means that the sense of perturbed instantaneous shear, in any horizontal direction, may differ from that of the bulk shear in that same direction.

## BULK DEFORMATION AXES

The average schistosity (Figs. 2 and 3) was shortened by asymmetric buckle folding (Ramberg 1963) and extended while reaching a WNW–ESE orientation (Fig. 8). The bulk shortening was accompanied by dextral bulk shear parallel to the fold-enveloping surfaces, which confines the early shortening axis ($e_3$) to a pair of quadrants bounded by the mean fold envelope and its normals (Fig. 8a). During subsequent bulk deformation, band boundaries, enveloping surfaces and material lines initially parallel to the shortening axis probably rotated by different amounts. These amounts cannot be reconstructed without knowing the path of bulk deformation.

At any instant of asymmetrical buckling, there must have been sinistral bulk shear at 90° to the mean fold envelope and therefore subparallel to the band boundaries (Fig. 8a). This contrasts with the dextral boundary-shear and associated clockwise rotation of the schistosity trace, both resulting from the buckle-strain perturbation. Evidently, the sense of perturbed shear rather

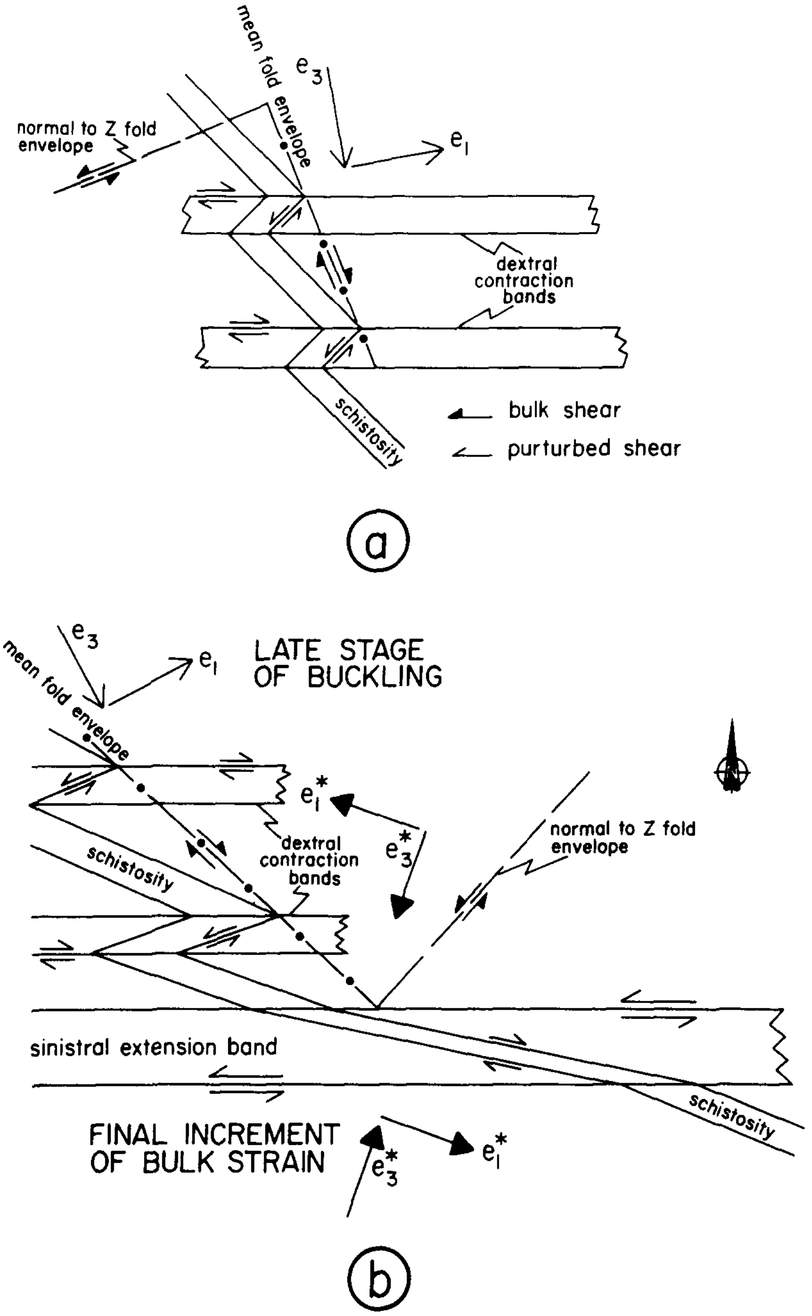

Fig. 8. (a) Orientation of principal axes of instantaneous strain ($e_1 > e_3$) which led to enhancement of low-amplitude Z folds. Note the deliberate omission of north arrow. (b) Axes of instantaneous strain at two stages of bulk deformation, (i) late stage of Z folding and emplacement of V2 veins and (ii) initiation of sinistral band structures (asterisks). Note the small angle between $e_3$ and the mean fold envelope, which is required for dilation veining but incompatible with bulk pure shearing (cf. a).

than that of bulk shear was reversed during subsequent WNW–ESE bulk extension (Fig. 8b).

The change from incremental shortening to incremental extension of the mean envelope implies that, near the end of bulk deformation, the folded schistosity rotated with respect to the principal axes (Fig. 8b). Depending on whether the deformational increment that produced the sinistral extension bands was biaxial or triaxial, the angle between the instantaneous shortening axis and the fold envelope has a minimum value of 45–53° (Ramberg 1959). The attitude and deformation of three sets of veins provide further constraints to the different stages of bulk deformation (Fig. 8).

## EMPLACEMENT AND DEFORMATION OF VEINS

Three generations of subvertical veins (V1, V2 and V3) have been identified in outcrop #1. The V1 (omitted in Fig. 2) are quartzo-feldspathic and transected by dextral contraction bands. They are closely folded in places (middle of Fig. 3), and seem to have experienced a clockwise rotation. These veins cut the schistosity, and appear to have buckled while the dextral band structures were generated.

Quartz veins (V2), which contain most of the gold at the Aubelle Mine, are effectively concordant to the E–W band structures (Figs. 3 and 5), and developed at a late stage of Z folding (Fig. 6). Given a set of coplanar weakness zones, the shortening axis need not be parallel to the walls of V2 structures, but must be subparallel to the mean fold envelope to come within 45° of the dilatant band boundaries (Fig. 8b). This precludes bulk pure shear and points to non-coaxial bulk deformation. V2 reduced the ease of schistosity-parallel glide, and probably led to the formation of sinistral extension bands.

The thickest V2 veins include fragments of schistose wall rocks, and contain much of the gold. The thinnest veins are composed of quartz or epidote fibres, and seem to have been formed by the crack–seal mechanism (Ramsay & Huber 1983). Relict trains of Z folds continue across some quartz veins (Fig. 6, lower middle part), and are indicative of replacement of wall rock along fractures. Even where discontinuous quartz veins occupy the middle region of dextral bands (V2 in Fig. 4), the geometry of Z structures is incompatible with hook folding (Hudleston 1989). In particular, hook structures are single-fold pairs in which the highest curvature is adjacent to the hinge-plane vein (Hudleston 1989).

V2 veins have been stretched and locally transformed into boudins or pinch-and-swell structures (Figs. 3 and 4). This may have started at a late stage of Z folding, and continued during the sinistral E–W shearing while the band structures were being extended (Fig. 8b).

V3 veins and associated fractures trend approximately NNE–SSW, and cut across schistosity, E–W band structures and earlier veins (Figs. 5 and 6). The veins are <1 cm thick and invariably barren. There is no macroscopic evidence to indicate that these veins have been strained, which suggests that they are coeval with, or later than, the sinistral extension bands (Fig. 8b). V3 veins are effectively perpendicular to schistosity and probably subparallel to the axis of final-stage shortening ($e_3^*$). This is plausible mechanically, because the schistosity was oriented in such a way that it could not have greatly influenced the orientation of extension cracks. Given the final orientation of the principal axes shown in Fig. 8(b), the envelope-parallel shear remained dextral.

## SUMMARY AND CONCLUSIONS

Two generations of E–W band structures and three vein sets are discernible in schistose metavolcanics at Aubelle Mine, Belleterre greenstone belt. The first bands are dextral contractional structures, whereas the second bands are extensional and sinistral. The local reversal in shear sense on material surfaces that finally reached an E–W orientation need not have occurred in a progressive simple shear regime. Instead, the reversal may have resulted from oblique superposition of two pure shears (tectonic pulses).

The first vein set (V1) pre-dates the dextral contraction bands, which are broadly coeval with the second vein set (V2). The orientation and unstrained condition of the third vein set (V3) suggest that it was generated by the same deformation increment which produced the sinistral extension bands.

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