Foreword

J. Duncan Keppie
(Editor)

During the period between 1981 and 1984, the eastern end of the Meguma Terrane was investigated under the Canada - Nova Scotia Co-operative Mineral Program. This program involved geologists from both Federal and Provincial Governments and a number of universities. It provided the first comprehensive remapping since the excellent mapping undertaken by E. H. Faribault around the turn of the century. The remapping was supported by airborne gradiometry and radiometry and formed the basis for multidisciplinary studies into various aspects of the geology , especially gold metallogeny. These studies, together with those in other parts of the Meguma Terrane, formed the basis for a Symposium at the Northeastern Section of the Geological Society of America in March, 1984. The papers in this volume represent a collection of several presented at the Symposium. Other papers on the topic have already been published in the Geological Survey of Canada Papers 83-1 and 84-1, the Nova Scotia Department of Mines and Energy Papers 83-1 and 84-1, and in the Canadian Institute of Mining and Metallurgy Division, Excursion Guidebook entitled "Gold Deposits in the Meguma Terrane of Nova Scotia", 1983. A symposium on "Turbidite-Hosted Gold Deposits" was held at the Geological Association of Canada Annual Meeting in Fredericton, 1985 followed by publication of a collection of papers in a Geological Association of Canada Special Paper. Some of these papers deal with gold deposits in the Meguma Terrane. A field trip to several gold deposits in the Meguma Terrane, augmented by a field guidebook, followed the Symposium. Undoubtedly, other results of these studies will continue to be published.

Each paper in this volume was reviewed by two independent reviewers whose comments were used to determine whether the paper was acceptable for publication. The editor takes this opportunity for thanking the reviewers for their assistance; their contribution lead to improvements in the papers. The reviewers were: J. Chandra, A. K. Chatterjee, D. B. Clarke, G. Cumming, K. Currie, J. Dostal, W. Fyson, S. J. Haynes, J. Henderson, R. V. Kirkham, H. Massone, B. H. O'Brien, K. H. Poulsen, P-Y Robin, D. F. Sangster, P. K. Smith, R. Thorpe, T. Wright and M. Zentilli. I would also like to thank P. Ledwidge for translating all but one of the abstracts.

Maritime Sediments and Atlantic Geology

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Constraints on the Origin of Gold in the Meguma Zone, Ecum Secum area, Nova Scotia

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Gold occurs mainly in laminated bedding-parallel quartz veins in the Goldenville Formation metawacke-slate sequence. The bedding-parallel veins formed by hydraulic fracturing before the beds were folded. Subsequently, during development of the folds, en echelon quartz veins formed on the fold limbs, and perhaps in the latest stage of folding, saddle reef veins formed along fold hinges. All these vein types are locally auriferous, but gold was first deposited during formation of the bedding-parallel veins. Absence of any through-going system of "feeder" veins as well as the formation of hydraulic fractures indicate that the rocks were not permeable during vein formation, and the quartz and gold were derived locally from the host strata.

L'or présent dans la suite métawacke-schiste de la Formation Goldenville est localisé principalement dans des veines de quartz laminées et parallèes à la stratification. Ces veines parallèes à stratification furent formées par fracture hydraulique avant le plissement des lits. Par la suite, pendant l'amplification des plis, des veines de quartz en échelon furent formées sur les flancs de plis et peut-être, pendant la phase finale de plissement, des veines en "gîte de selle" se formèrent à la charnière de plis. Tous ces types de veines sont aurifères par endroit mais l'apport initial de l'or date de la formation des veines parallèes à la stratification. L'absence de système de veines nourricières ainsi que la formation de fractures hydrauliques indiquent que les roches n'étaient pas perméables à l'époque de formation de veine et que le quartz et l'or sont de provenance locale.

INTRODUCTION

Disseminated visible gold occurs in quartz veins in the Goldenville Formation of the Cambro-Ordovician Meguma Group (Fig. 1). In the Meguma Zone between Sheet Harbour and Goldenville, one principal vein set is commonly subparallel to bedding, a second vein set forms en échelon arrays within slate interbedded with thicker arenaceous metawacke, and a third set occurs perpendicular to fold hinges within some metawacke beds. The conformably overlying Halifax Formation is mainly slate with thin silty metawacke beds, and generally does not contain quartz veins. Only the bedding-parallel and en échelon veins appear to be auriferous in the study area.

Auriferous veins occur in rocks of greenschist to lower amphibolite metamorphic grade. The typical vein in greenschist terrain is composed of coarse quartz, with some carbonate, chlorite and white mica. Arsenopyrite comprises less than 10 percent of the auriferous veins, and arsenopyrite porphyroblasts are scattered throughout the adjacent wall rocks.

Our main purpose in this report is to describe the relationship of the bedding-parallel veins to the host Goldenville Formation and their development within the geological history of the Meguma Zone. Several explanations of the origin of these veins have been proposed by past workers. Since the last century, bedding-parallel veins in the Goldenville Formation have been classified as anticlinal saddle reefs, first adopted by Faribault (1899) and
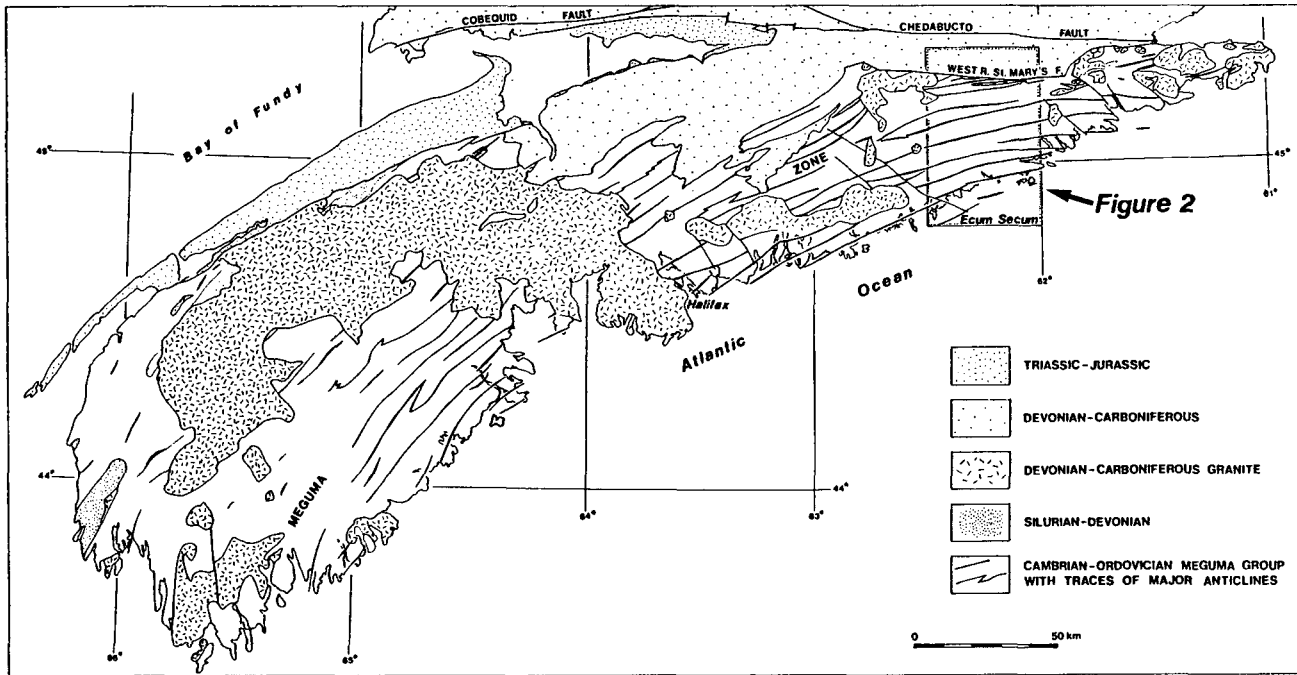
Figure 1 - Generalized geological map of part of mainland Nova Scotia showing the Meguma Zone and the location of the Ecum Secum study area.

recently accepted by Keppie (1976). It is now known that saddle reefs form late in the strain history of chevron folding, and are restricted to dilatant openings in fold hinge regions (Ramsay, 1974). Our studies show that the auriferous bedding-parallel veins in the Goldenville Formation are not restricted to fold hinge regions and that the bedding-parallel veins actually antedate the folding.

Recently it has been proposed that some or all of the bedding-parallel quartz in the Goldenville Formation originated as sea-floor hydrothermal vent-apron deposits of siliceous sinter (Haynes, 1983) or deposits from silica-rich brine (Kretschmar, 1984). Bedding-parallel quartz in the Goldenville Formation consists of centimetric crystals with their prism axes commonly aligned subnormal to the walls of the veins (Henderson, 1983a) whereas sinters are amorphous. Neither Haynes (1983) nor Kretschmar (1984) supported their hypotheses with arguments to explain the crystallization of amorphous silica to form coarse, oriented quartz crystals under greenschist grade conditions. It

is noteworthy that James (1955) used grain size of crystallized chert in banded iron formation as an index to metamorphic grade: an average grain size of 0.2 mm defined the staurolite-to-sillimanite grade transition in the Penokean Orogen in northern Michigan.

Graves and Zentilli (1982) proposed that bedding-parallel veins in the Goldenville Formation resulted from hydraulic fracturing under orogenic stress during greenschist grade metamorphism. Their model assumes that fluids released by dehydration reactions could not escape rapidly enough to prevent pore fluids from exceeding the local tectonic stress. Henderson (1983a) attributed inclusion bands of white mica in quartz crystals within bedding-parallel veins in the Goldenville Formation to the crack-seal mechanism of rock deformation (Ramsay, 1980), and thus supported the hydraulic fracture model of Graves and Zentilli (1982).

Smith (1983) showed that at Cochrane Hill (Fig. 2) some auriferous quartz veins antedate and some postdate late Acadian garnet grade metamorphism, and
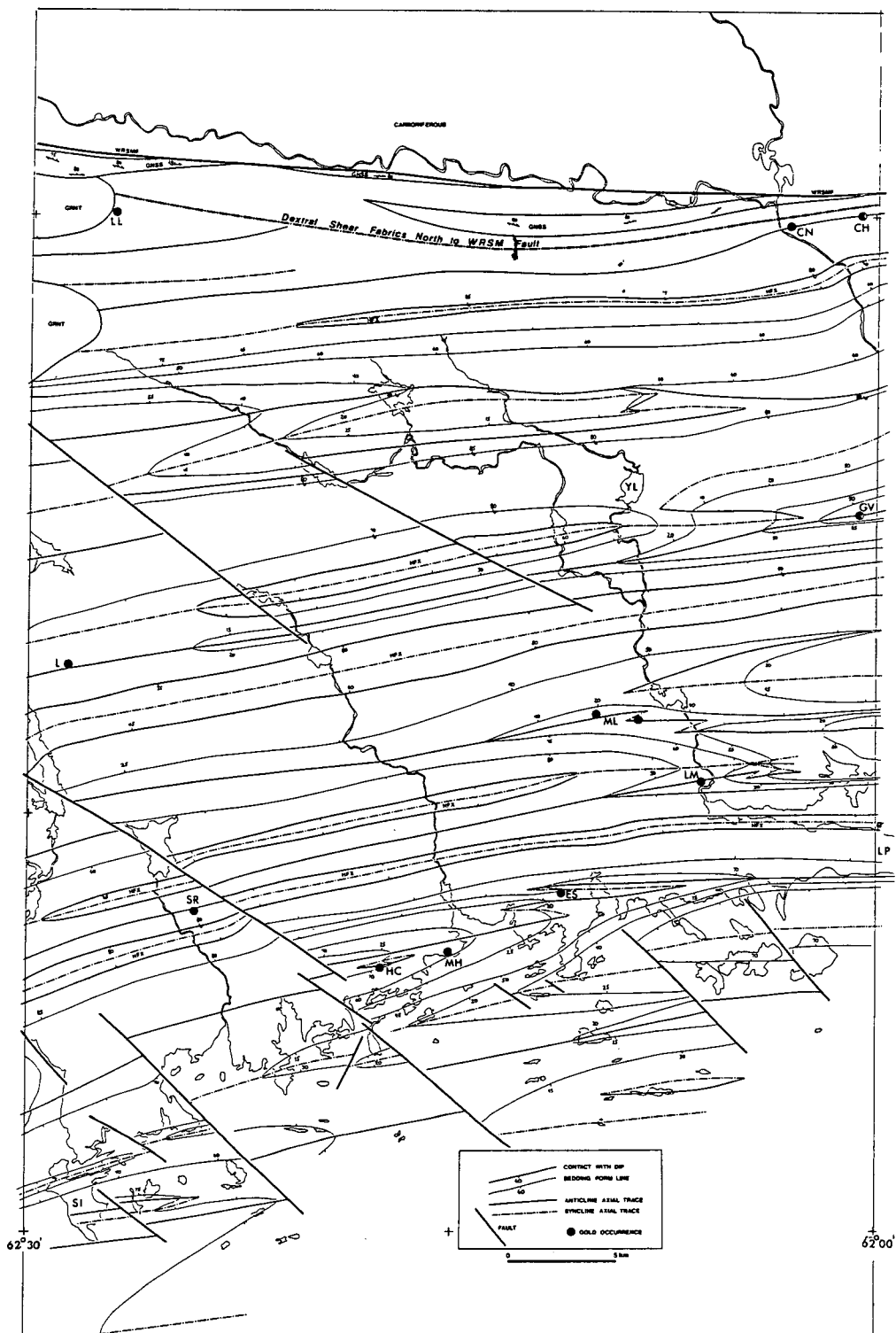
Figure 2 - Geological map of the Ecum Secum study area. Carboniferous fanglomerate (Horton Group)
occurs in the St. Mary's Graben north of the West River-St. Mary's River (WRSMF). South of WRSMF the
Meguma Group, composed of the Goldenville Formation overlain by the Halifax Formation (HFX), is
intruded by granite bodies of two textural types: unfoliated granite (GRNT) and foliated granite
(GNSS). Gold occurrences within the area are: Salmon River (SR), Harrigan Cove (HC), Moosehead
(MH), Ecum Secum (ES), Liscomb Mills (LM), Miller Lake (ML), Goldenville (GV), Cochrane Hill (CH),
Crow's Nest (CN), Liscomb Lake (LL), and Lochaber (L).

concluded that gold was deposited several times during the deformational and metamorphic history of Meguma Zone rocks in this area. The relative age of first development of auriferous quartz veins in the Goldenville Formation would place constraints on some genetic models that have been advanced. Once introduced into the vein network, gold may have later migrated with quartz into other sites, or alternatively, gold may have been introduced from one or more sources several times during the history of vein formation.

CLASSIFICATION OF VEINS IN THE GREENSCHIST TERRAIN

The Meguma Group in the Ecum Secum area consists of Goldenville Formation metawacke and some slate, overlain by Halifax Formation slate and thin bedded silty metawacke. The two units have been folded into tight sub-vertical regional en échelon folds (Fig. 2). Grade of regional metamorphism is lower greenschist except in the north along the West River – St. Mary's Fault where staurolite grade static metamorphism has been superimposed on folded strata which were then redeformed by dextral shear. Within the less complicated greenschist terrane to the south, we recognized three distinct geometries of veins based upon their relationships to bedding and folds, namely, bedding-parallell (BP), en échelon (EE) and ac veins (Fig. 3). In contradiction to our earlier report (Henderson, 1983b), subsequent field work showed that BP and EE veins are not contemporaneous: the BP veins antedate the folding, and the EE veins formed throughout the folding history. The ac veins formed late in the folding history and in some fold hinges ac are weakly folded as a result of vein-parallel shortening.

An example of the classical saddle-reef vein was not observed in our study area. Nevertheless, the major orebody in the Salmon River Gold District (Dufferin Mine) was a rich quartz lode 6 m thick on the crest of an anticline that pinched out within 37 m down-dip
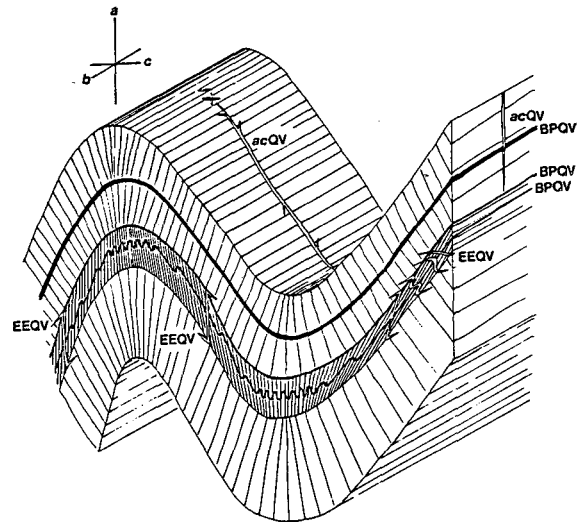

Figure 3 - Diagrammatic representation of the geometry of bedding, cleavage and the three principal vein sets: BPQV (bedding-parallel quartz veins), EEQV (en échelon quartz veins) and acQV (veins parallel to the ac or profile plane of the folds). Note that the drawing is not to scale; most veins are several centimetres wide and several hundred metres long whereas the fold wave lengths are several kilometres.

on each limb (Fig. 4), and was mined for 545 m along the fold crest (Malcolm and Faribault, 1929). Another vein type recognized by Faribault, but not directly observed in our study is the ab vein or fissure vein. At Ecum Secum Mine, the Galena Fissure Vein was coincident with the axial surface of a minor syncline (Fig. 5) and was probably an ab vein. There too, several BP veins (Cameron Leads) are thickened considerably by isoclinal folding in the hinges of a minor syncline and anticline: a process of mechanical thickening of veins which otherwise were too thin to mine with profit on the limbs of folds.

Bedding Parallel Veins (BP)

BP veins are widespread. Most commonly they occur in slate at or near the top of a complete or incomplete Bouma turbidite cycle. They also occur between thick amalgamated metawacke beds. Although BP veins commonly
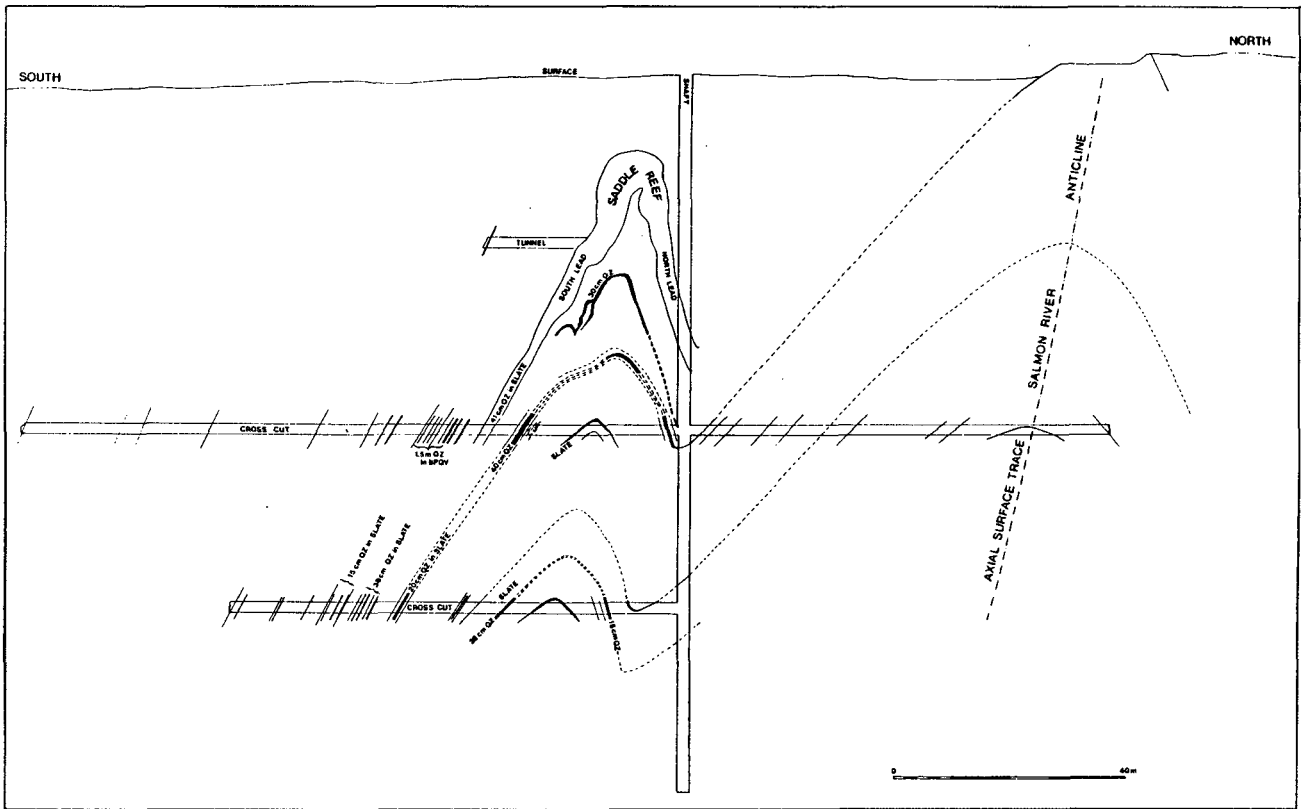
Figure 4 - Transverse-section of the Dufferin Mine, Salmon River Gold District (traced from an unpublished original drawing by E.R. Faribault, Geological Survey of Canada, 1899).
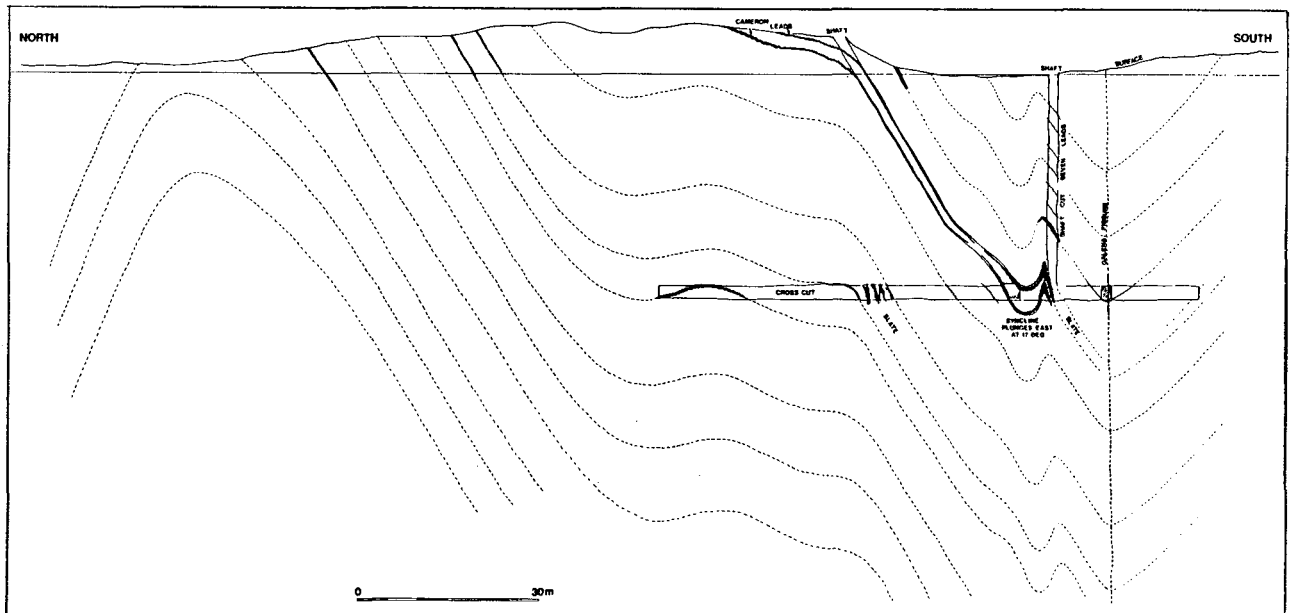
Figure 5 - Transverse-section of the Ecum Secum Mine (traced from an unpublished original drawing by E.R. Faribault, Geological Survey of Canada, 1903).

parallel bedding for considerable distances, locally they are discordant and truncate primary fabrics within the turbidites, e.g. climbing-ripples and sand filled scours. The BP veins range in width from several millimetres to a metre; most are about 10 cm thick and several veins may occur in the same slate bed.

Mesoscopically, BP veins are composed of fairly coarse, translucent quartz, and commonly are subdivided by laminations composed of dark micaceous material (inclusion bands) parallel to the vein walls (Fig. 6). In the gold districts these veins may also contain coarse carbonate, disseminated arsenopyrite, pyrite, pyrrhotite, galena and visible gold.

In some BP veins, stylolitic surfaces parallel the vein walls (Fig. 7) and, along with the micaceous inclusions, contribute to the vein-parallel fabric. The stylolitic surfaces show parallel grooves or striations that most commonly are subparallel to the dip of the veins (Fig. 8). Their micaceous and lineated character favours simultaneous development during folding by pressure solution (to produce the

linear surface structure). Although striations appear on the surface of all stylolitic laminations within the veins, striations on different surfaces within the same vein may not be exactly parallel and may differ by as much as 30 degrees. In addition, some veins contain millimetric layers of alternating milky and clear quartz which are oriented perpendicular to the vein walls and appear to intersect the vein surface parallel to the surface striations (i.e. parallel to the $\underline{ac}$ plane). Marcos Zentilli (personal communication, 1983) drew our attention to this relationship, and suggested that the milky layers might have a higher density of fluid inclusions than the clear layers. Thin sections of veins cut perpendicular to both surface striations and parallel vein-normal, colour-banded quartz fabric confirm that planes of fluid inclusions are aligned normal to the vein walls, but we could see no correlation between planes of dense fluid inclusions and the colour banding. Evidence of stretching in $\underline{a}$ and $\underline{b}$ directions is present in some BP veins, including pinch-and-swell as well as boudinage with stubby quartz crystals aligned parallel to $\underline{a}$ and $\underline{b}$.
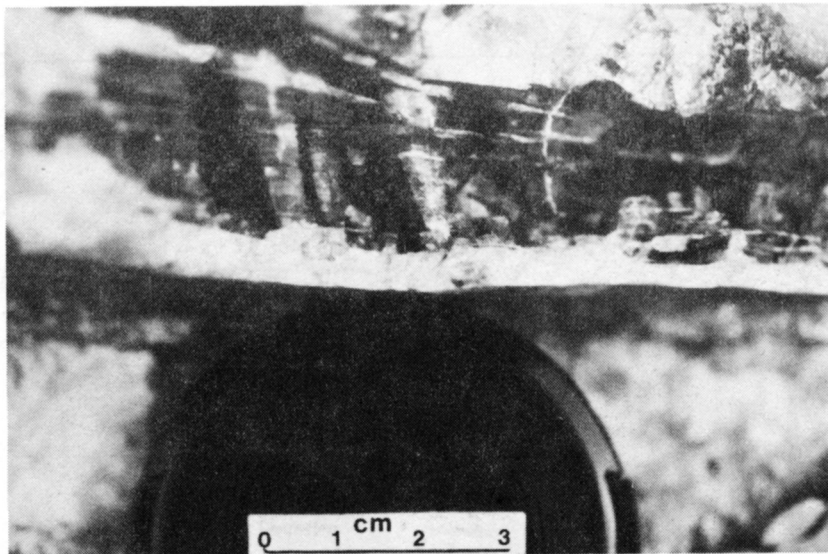

Figure 6 - Photograph showing a vertical laminated BPQV at Harrigan Cove Mine. Note the euhedral quartz crystals with numerous laminations parallel to their bases. The void space probably contained carbonate. GSC 204124-D
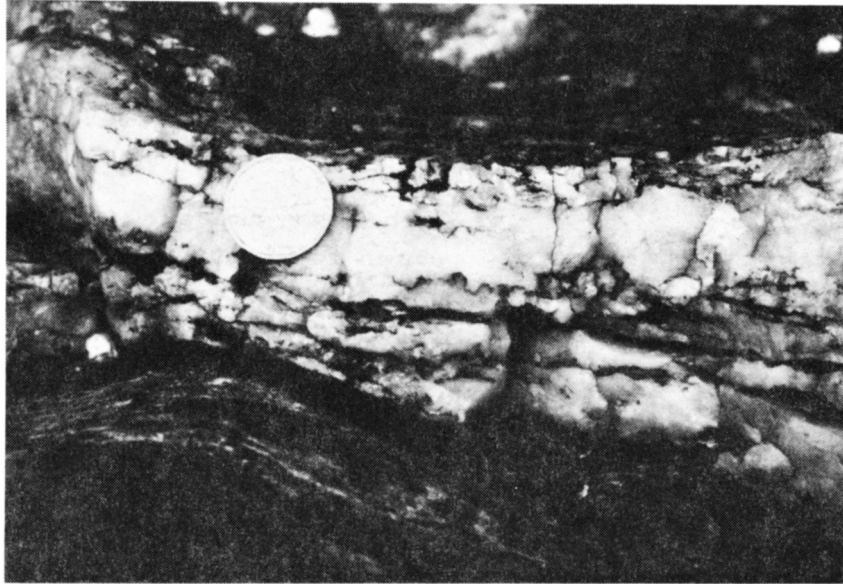
Figure 7 - Photograph of a horizontal exposure of a steeply-dipping BP quartz vein showing stylolitic laminae. Note also the down-dip pinched portion of the vein. The outcrop is located at Markie's Point on the east coast of Sober Island (SI on Fig. 2). GSC 203683-X

Figure 8 - Photograph of a vertical BP vein showing down-dip grooves on stylolitic laminae. The outcrop is located on the west coast of Liscomb Island, 2 km east of Liscomb Peninsula (LP on Fig. 2). GSC 204124-A

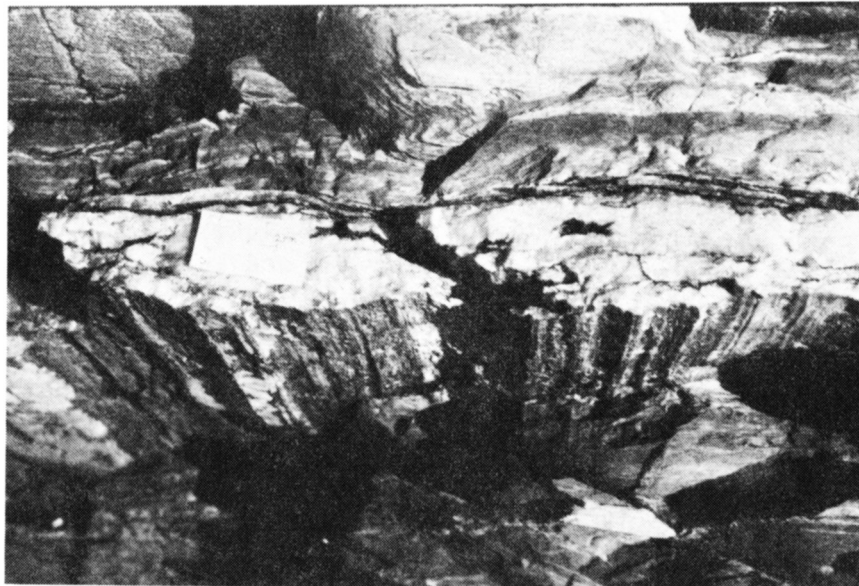BP veins in slate beds are isoclinally folded on the hinges of major folds. The folded veins maintain constant thickness and are considered to be buckle folds; a few measurements of buckle shortening of veins in the ac plane ranged from 50 to 60 percent. However BP veins between amalgamated metawacke beds in fold hinges are not folded.

In thin section, primary quartz crystals in BP veins show various degrees of strain, from undulose extinction to subgrain formation and to total obliteration of primary features by recrystallization (Fig. 12). The quartz laminae and inclusion bands parallel to the vein walls (Fig. 9, 10, 11) are present in non-recrystallized quartz and are therefore primary growth features. The spacing between laminae is about 50 microns. They are separated mainly by white mica and some chlorite a few microns thick with their cleavage planes mainly subparallel to the laminae and vein wall. Also, pelitic fragments believed to be detached pieces of wall rock are contained within the laminated BP veins. The mica inclusion bands are continuous across quartz grain boundaries; the quartz grains which contain them average 5 mm in width at the vein wall and 1 cm in length. If, as described by Ramsay (1980), the inclusion band micas grew syntaxially on wall-rock micas (see also Cox and Etheridge, 1983, and van der Pluijm, 1984), it would appear that the BP veins were initiated when the wall-rock micas still possessed a bedding-parallel depositional fabric (i.e. before formation of slaty cleavage). A pre-cleavage initiation of growth of at least some BP veins is supported by a SEM scan (David Walker, Geological Survey of Canada, analyst) of a pelitic wall-rock inclusion from the vein at Harrigan Cove Mine (Fig. 6): only a weak bedding-parallel mica fabric is present.

Quartz c-axis orientation measured using a standard technique with the universal stage, and c-axis traces measured on a flat stage with a gypsum plate method (Garcia-Celma, 1982) show preferred orientation either normal to the vein wall (Fig. 9), or between 45 degrees and the normal to the vein wall (Fig. 10). The c-axes commonly parallel quartz crystal boundaries and have the same degree of obliquity to the vein walls.

In some cases, as in the BP vein shown in Figure 11, the c-axis traces make a smaller angle with the inclusion bands and the vein wall than do the crystal boundaries. In his study of various crack-seal veins, Ramsay (1980) observed that grain boundaries and c-axes of fibrous quartz are not necessarily parallel, although the orientation of long fibrous crystals may record relative motion between vein walls during crystal growth. We think that the primary quartz in the BP vein shown in Figure 6 is not fibrous (Durney, 1972; cf. Durney and Ramsay, 1973, p. 67-96), but rather the quartz crystals grew across the walls of a fluid-filled fracture that periodically opened along the contact between vein and wall rock.

In summary, we can say from our microfabric observations that the BP veins formed by incremental hydraulic fracturing at the vein-wall rock contact during bedding-normal extension at the onset of horizontal shortening that subsequently produced the slaty cleavage and later the folding. The c-axes in the least strained sample (Figs. 6 and 9) are nearly perpendicular to the vein walls; the oblique relationship between c-axes, crystal boundaries and vein walls in some samples may indicate oblique growth of quartz crystals across a fluid-filled crack, or the quartz crystals may be coarse fibres. Parallelism of bedding micaceous inclusion bands suggests that at least some of the BP veins formed when the micas still had a primary bedding-parallel fabric (i.e. before development of slaty cleavage). Steeply-dipping veins with down-dip grooves on stylolitic laminae reflect
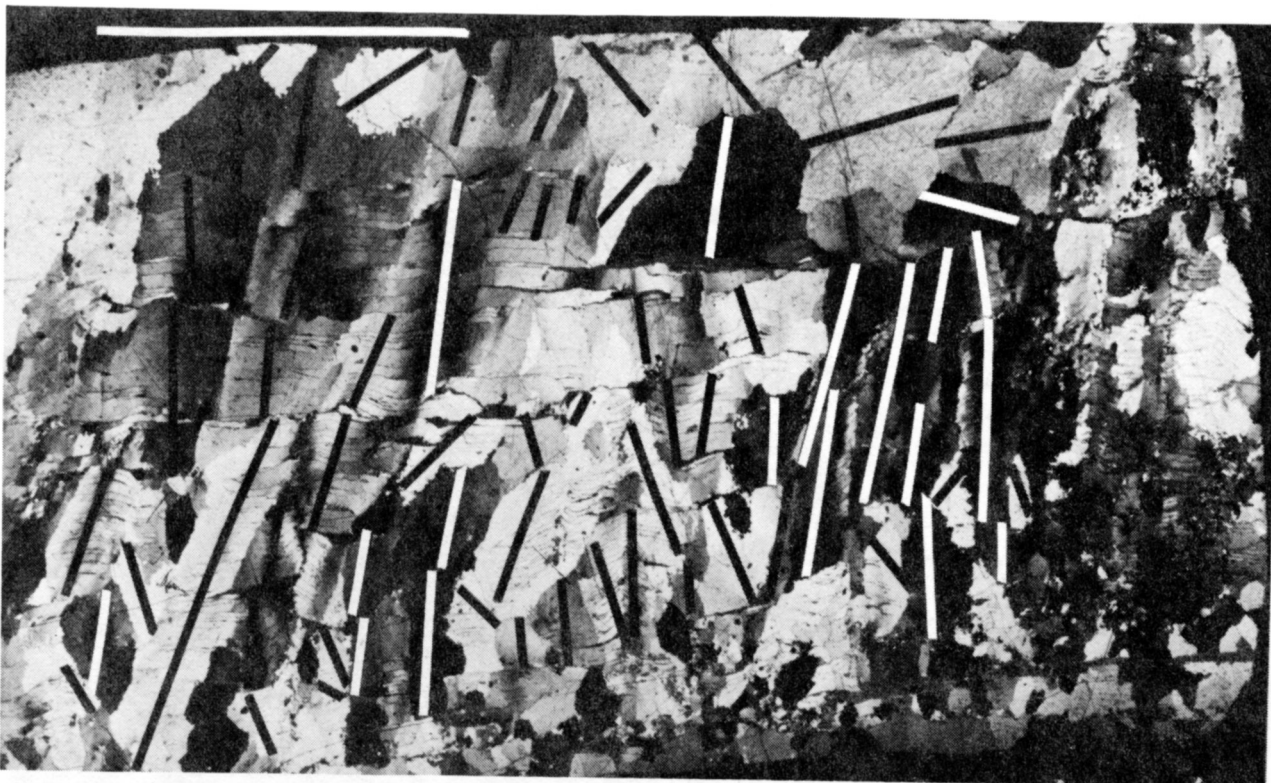
Figure 9 - Photomicrograph of a thin section (cross nichols) of a BP vein at Harrigan Cove Mine (Fig. 6) cut normal to the vein walls, showing the traces of c-axes of quartz crystals (white and black bars). Note the tendency for the c-axes as well as the crystal boundaries to be perpendicular to the laminae which are outlined by trails of white mica, chlorite and opaque material (inclusion bands). The bar scale is 1 cm long. GSC 202510-P

bedding-parallel shear during flexural folding subsequent to BP vein formation. A more extensive petrofabric study using a universal stage on both primary and recrystallized quartz is necessary to document and interpret more completely the primary and secondary features of the BP veins.

En Échelon Veins (EE)

The EE quartz veins occur only on fold limbs; most EE veins lie within slate and silty slate and pinch out in metawacke above and below the slate. The EE veins formed throughout the folding process. Arrays of fluid-filled extension fractures became filled with quartz and later underwent bedding-parallel shear. In Figure 3 the EE veins on the right-hand limb of the syncline depict a sequence of decreasing age from right to left.

During continuing deformation, a nearly planar vein became more shortened, rotated and elongated as the syncline tightened. Note that in the $\underline{ac}$ plane the orientation of the terminations or "pins" of the veins in the bounding metawacke beds reflects the original orientation of the EE vein relative to bedding and the axis of compression during fracture formation: the acute angle between bedding and the axis of the short pin indicates the shear direction of the metawacke beds bounding the slate interbed. Because the pins most commonly are not detached from the EE vein segments passing across the metawacke-slate interface we can certify that generally there was no loss of cohesion between the metawacke and slate across the contact bedding plane during folding. In Figure 13 a relatively old EE vein is shown in its present attitude relative to bedding and cleavages, as well as its apparent
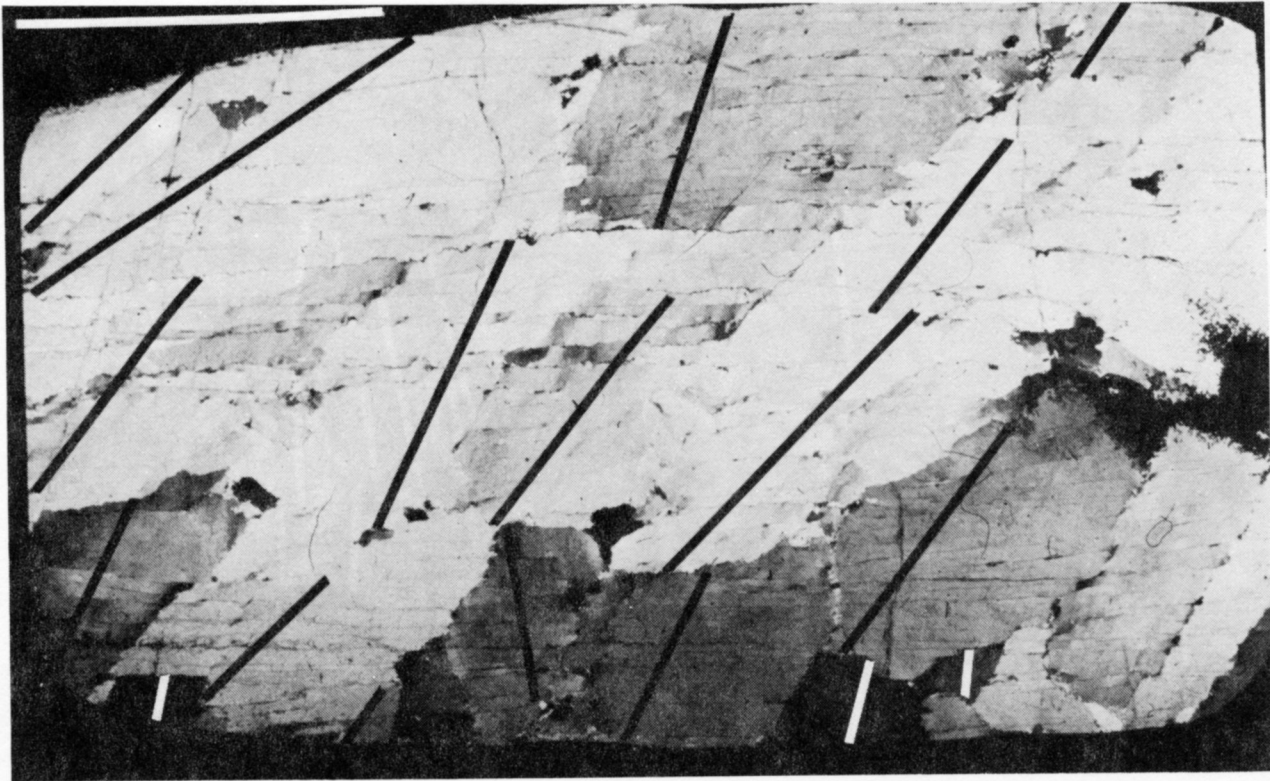
Figure 10 — Photomicrograph of a thin section (cross nichols) of a BP vein from about 2 km NW of Goldenville showing the trace of c-axes of quartz crystals. The thin section is cut parallel to the ac plane. Note the tendency for the c-axes to parallel the crystal boundaries which are oblique to the laminae. The bar scale is I cm long. GSC 202510-I

original relationship when bedding and cleavage were originally perpendicular. The dip of bedding at the time of fracturing in this example is not known.

Mesoscopically, EE veins are characterized by coarse milky quartz with rare scattered aggregates of coarse carbonate and chlorite. The veins are nowhere laminated or corrugated like many BP veins. As a group, EE veins have widths ranging from less than 1mm to as much as 1m. Individual EE veins themselves vary considerably in width, and commonly the widest parts are within the centre of the slate bed. The EE veins were formed during the folding and therefore postdate the BP veins.

Although we did not identify an unequivocal EE vein in any of the existing surface exposures at the specific gold deposits shown in Figure

2, we are fairly certain that Hedley's (1941) description of "angulars" in the Guysborough Mine at Goldenville corresponds to our type EE veins. It is worth noting that the richest orebodies in the Guysborough Mine occurred in angular veins near where they intersected the "leads" (our type BP veins).

ac Veins

In contrast to BP and EE veins which lie between bedding planes or are confined within slate beds, ac veins occur exclusively in metawacke beds. They are vertical and strike north-south. Traced parallel to strike, some ac veins terminate in conjugate sets of short veins aligned en échelon beyond the tip of the principal ac vein (see the diagrammatic representation in Fig. 3). In the northern half of the study area many ac veins show vein-parallel buckle shortening of 10 to 15 percent,
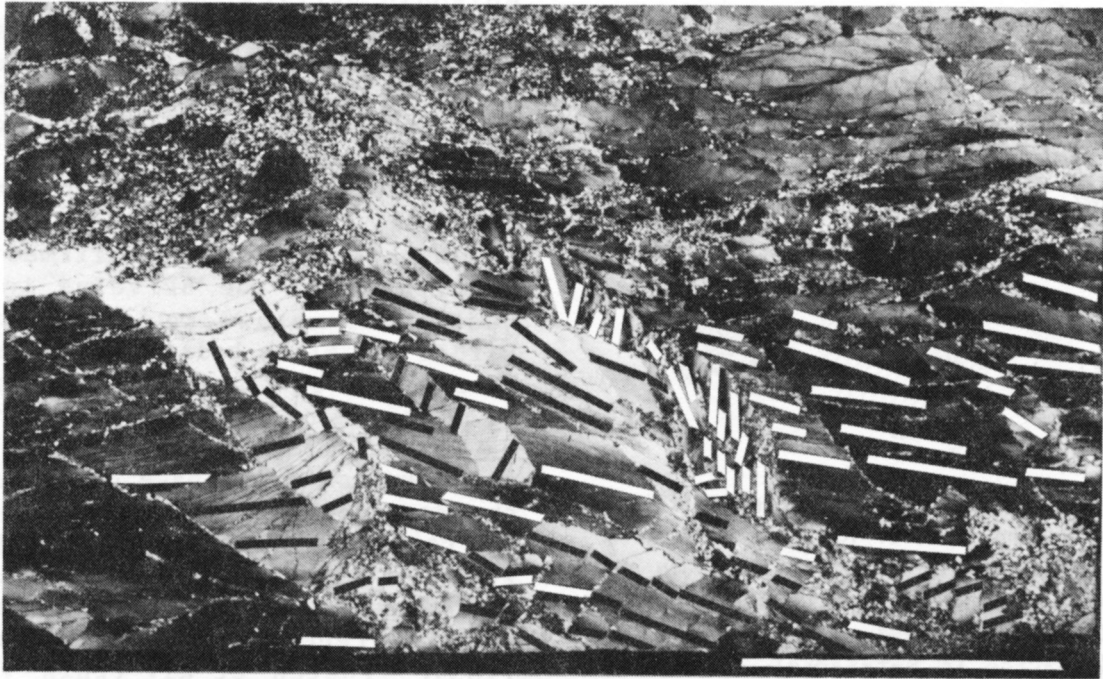
Figure 11 - Photomicrograph of a thin section (cross nichols) of a BP vein from Liscomb Island (Fig. 8) showing the trace of c-axes of quartz crystals. The thin section is cut parallel to the ac plane. Note the kinking of the laminae and the tendency for the c-axes traces to lie subparallel to the laminae whereas the primary crystal boundaries lie at a larger angle to the laminae. The bar scale is 1 cm long. GSC 202510-Q
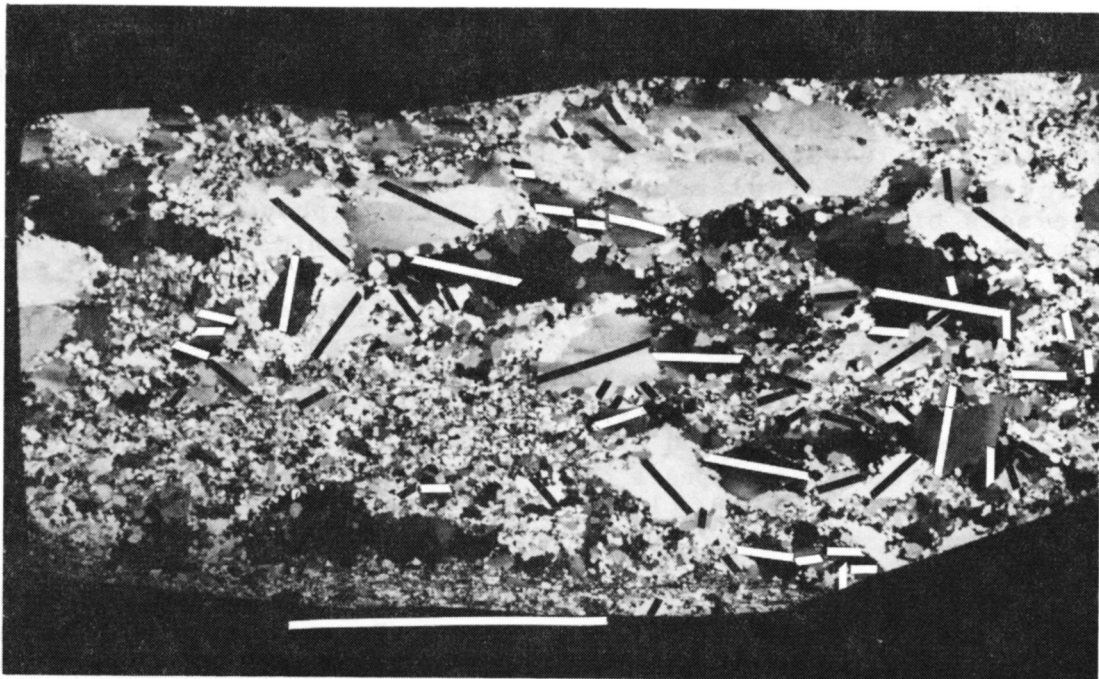

Figure 12 - Photomicrograph of a thin section (cross nichols) of a BPQ vein from the region of overturned beds 2 km west of Yankee Lake (YL on Fig. 2). The thin section is cut parallel to the ac plane. Note the apparent absence of a preferred orientation of the quartz c-axes traces in the large grains as well as the absence of laminae. The bar scale is 1 cm. GSC 202510-K
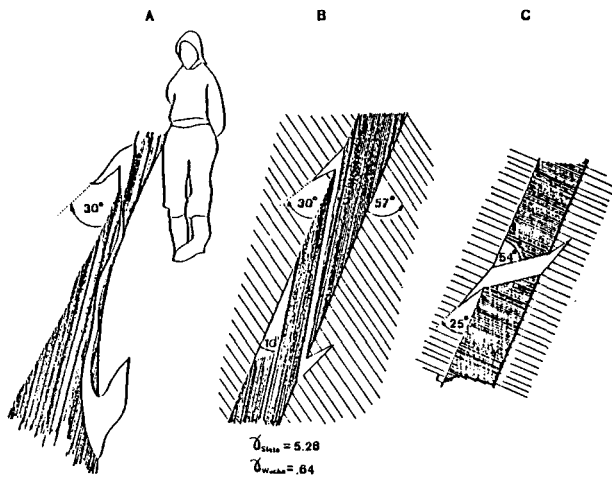
Figure 13. Deformation of an EE vein within a slate bed during flexural folding. A. Tracing from a photograph of an EE vein in slate and metawacke from the southeast coast of Goose Island (close-spaced cleavage in slate, wide-spaced cleavage in metawacke). B. Scaled drawing of bedding-cleavage-vein relations measured in the outcrop. C. Restoration of the EE vein to its original form assuming that the vein filled an en échelon extension fracture in the slate at the onset of flexural folding when bedding and cleavage were originally perpendicular (see Henderson, 1983b); simple shear strains in the slate and metawacke are indicated.

and in the southern half of the study area ac veins in fold hinge regions where bedding and cleavage are nearly perpendicular, are displaced by conjugate sets of kink bands in the vertical spaced cleavage of the metawacke.

The ac veins are composed of coarse crystals of milkly quartz commonly arranged normal to the vein walls. The veins are not laminated or grooved like the BP veins, and the quartz appears to have grown across fluid-filled extension fractures.

DISCUSSION OF CONSTRAINTS ON THE ORIGIN OF GOLD

The earliest gold is found in laminated BP quartz veins that resulted from the crack-seal mechanism of rock deformation. The veins grew by episodic vertical hydraulic extension, fracturing and concomitant vein mineral precipitation at the onset of bedding-parallel shortening. In order for the fluid pressure to exceed the lithostatic pressure the permeability of the rocks must have been very low. Absence of permeability in both metawacke and slate is affirmed by the occurrence of the BP veins in slate just below metawacke beds as well as within the slate beds. The development of cleavage by the growth of quartz and mica beards on detrital grains within metawacke during greenschist metamorphism would have contributed to the destruction of primary pore-space. The cogenesis of cleavage and extension veins is well documented in the geological literature (see for example the references cited by Etheridge, 1983). Fueten et al. (this volume) demonstrated that formation of spaced cleavage in metawacke in the study area resulted in substantial loss of silica, some of which was probably precipitated in the veins. However, absence of slaty cleavage in a pelitic inclusion within a BP vein indicates that the vein began to be formed before the development of cleavage.

No textural evidence supports the notion that bedding-parallel quartz (and its contained gold) in the Goldenville Formation was originally a bed of amorphous silica. Epigenetic sulfur, arsenic and gold may have been deposited initially in metawacke (Crocket et al., this volume) and thence were mobilized in hydrous solution with silica, carbonate, mica, chlorite and arsenopyrite and deposited in nearby BP veins at the onset of horizontal compression and vertical extension. During folding, EE fractures formed on fold limbs, and were enriched in gold where the EE fractures intersected auriferous BP veins. Regardless of whether gold in the study area is polygenetic, we conclude that quartz, gold and other vein minerals are of local origin and probably were in a more dispersed form within the turbidites before being concentrated initially in the BP veins.

There is not evidence of "feeder" veins by which hydrothermal solutions introduced the vein minerals to the veins from some source below the Goldenville Formation.

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