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Origin of bedding-concordant auriferous quartz veins, Meguma Terrane, Nova Scotia

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Controversy surrounds the question of origin of bedding-concordant auriferous quartz veins occurring in Meguma Group rocks of Nova Scotia. Several origins have been proposed, most important among which are 1) that the veins formed pretectonically due to precipitation from submarine hydrothermal hot springs, and 2) that the veins are syntectonic and due to precipitation into hydraulic fractures from aqueous solutions. The fundamental differences between these two proposed origins have obvious consequences for studies of quartz and gold genesis and their location in this area.

Microstructures of bedding-concordant veins from a number of localities in the Meguma Terrane show conclusive evidence of a syntectonic, multiple-hydraulic fracturing origin for the veins studied, and lend no support to the hot springs hypothesis.

On retrouve, dans les roches du groupe Meguma de la Nouvelle-Ecosse, des veines de quartz aurifères, parallèles à la stratification, dont l'origine demeure un sujet controversé. Plusieurs modes de formation ont été proposés dont les principaux sont: 1) un emplacement précédant l'événement tectonique, par précipitation à partir de sources chaudes hydrothermales sous-marines; et 2) un emplacement syntectonique le long de fractures hydrauliques, par précipitation à partir de solutions aqueuses. Les différences fondamentales marquant ces deux modes d'origine ont des conséquences importantes quant à l'étude de la genèse du quartz et de l'or ainsi qu'à leur présence dans cette région.

Plusieurs sites dans le terrain Meguma font voir des veines concordantes à la stratification caractérisées par des microstructures qui indiquent de façon concluante l'origine syntectonique, par fractures hydrauliques multiples, de ces veines. L'hypothèse des sources chaudes est donc écartée.

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INTRODUCTION

The Meguma Terrane of Nova Scotia (Fig. 1) has yielded approximately one million ounces of gold from many different localities. Almost all of the gold was found in quartz veins, basically concordant to bedding in the host rocks, though locally cross-cutting it. These concordant quartz veins very commonly possess a complex internal structure, being laminated parallel to their contacts with the host rocks and showing development of a 'columnar' structure in places, the 'columns' more-or-less perpendicular to the vein contacts (Malcolm 1929).

Several hypotheses dealing with the origin of these veins have been proposed. The present controversy over the veins' origin is due to fundamental differences between two favoured hypotheses, and the important consequences of either hypothesis on questions of gold genesis and location. The two hypotheses are:

1) the bedding-concordant auriferous quartz veins are pretectonic, derived from deposition of siliceous sinter on the ocean floor around submarine hot springs, subsequently metamorphosed; and

2) the bedding-concordant auriferous quartz veins are syntectonic, produced by precipitation from aqueous solutions into hydraulic fractures.

Bedding-concordant quartz veins from eight localities in the central and eastern parts of the Meguma Terrane (Fig. 1) were examined in outcrop and sampled. Thin sections were cut in order to study vein microstructures, to collect evidence which might confirm or deny one or other of the prevailing hypotheses, or suggest further alternatives.

GENERAL GEOLOGY

The Cambro-Ordovician Meguma Group of Nova Scotia is divided into two forma-

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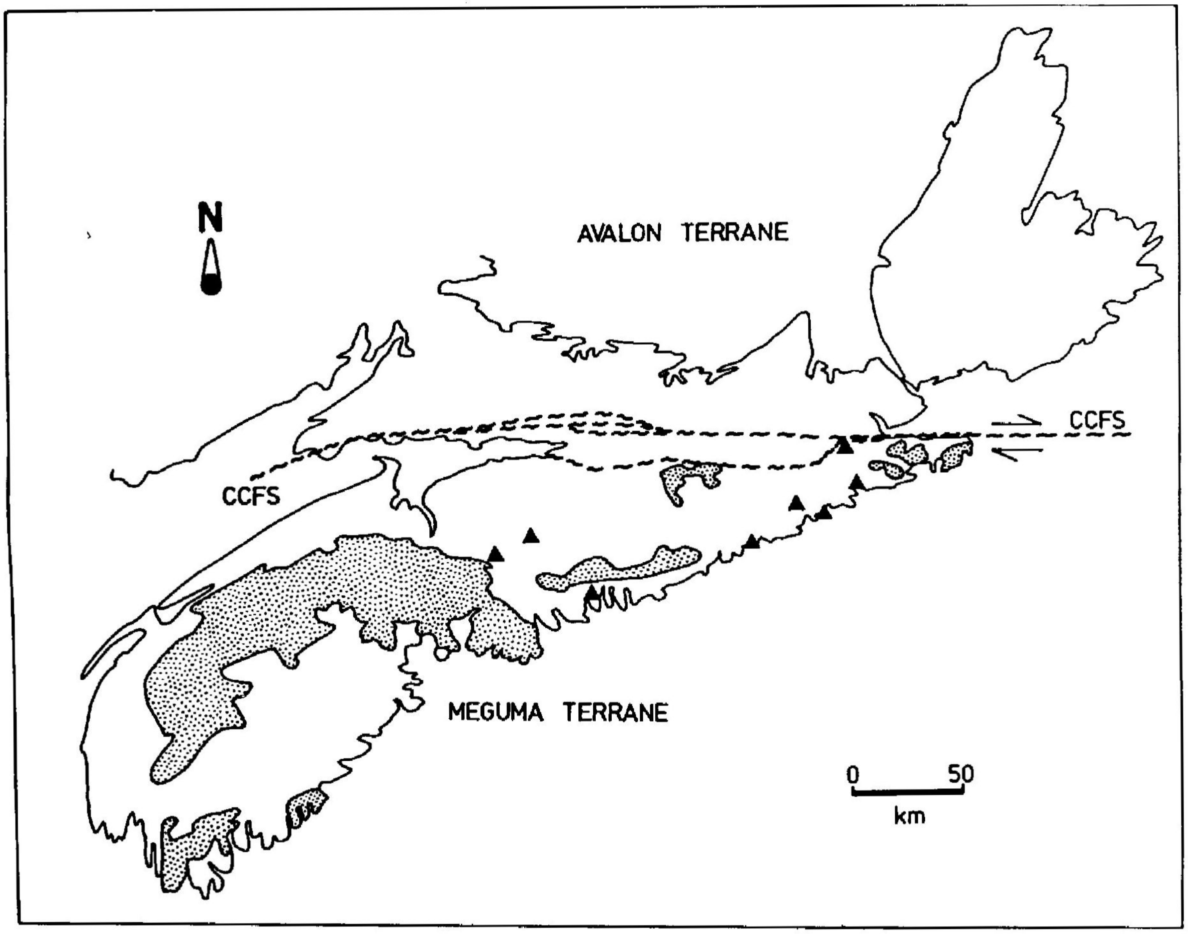

Fig. 1 - Meguma Terrane of Nova Scotia, solid triangles show localities of studied quartz veins. CCFS - Cobequid-Chedabucto Fault System. Stippling indicates major granitoid bodies.

tions, the basal sandstone-rich Goldenville Formation and the upper slate/phyllite-rich Halifax Formation (Schenk 1971, 1976). The bedding-concordant auriferous quartz veins generally occur in the Goldenville Formation, close to the Goldenville/Halifax boundary (Malcolm 1929) and very commonly are found in slate beds. There is an obvious structural association with the location of the auriferous veins. They occur associated with the hinge areas of elongate anticlinal domes, and especially within minor parasitic anticlinal domes or flexures on the major dome flanks (Malcolm 1929, Mawer 1985). The anticlinal folds which contain the auriferous bedding-concordant quartz veins vary considerably in tightness, being generally open to tight in the central and southern part of the Meguma Terrane, and generally tight to isoclinal in the eastern part of the terrane. At the macroscopic scale the folds' hinge lines are roughly horizontal, at a smaller scale the folds are doubly plunging though the angle of plunge is not great. The folds' axial surfaces are steeply-dipping to vertical.

The bedding-concordant veins in outcrop and hand-sample are structurally complex. As mentioned previously, most of the veins are laminated. This lamination is of two sorts, a fairly coarse lamination defined by intercalated layers of quartz and layers and elongate fragments of slate aligned subparallel to the vein walls (Fig. 2), and a much finer-scale lamination defined by thin, closely-spaced phyllosilicate films (Fig. 3), which closely mimic the vein wall topography. Many of the veins possess several jagged, though more-or-less planar structures, which are asymmetrically and irregularly spaced across the vein thickness, are subparallel to the vein

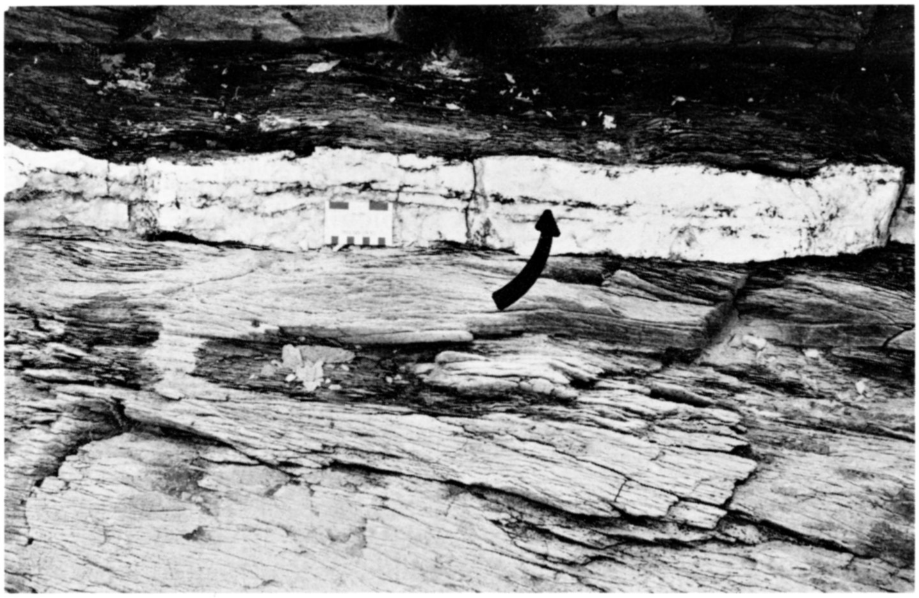

Fig. 2 - Bedding-concordant quartz vein, elongate fragments of slate arrowed. Note that the wall rocks contain an intense cleavage, the trace of which is slightly acute to bedding. Location - Wine Harbour.

walls, and truncate the finely-spaced phyllosilicate lamination (Fig. 3). Where not strongly deformed and recrystallized, the veins locally have a 'columnar' structure approximately perpendicular to the vein walls (Fig. 4). Commonly, the veins show pinch-and-swell structure and are locally boudinaged. In three-dimensional exposures the layer-parallel components of extension implied by these structures are seen to have operated both horizontally and to a lesser extent down-dip (ie. 'chocolate tablet' pinch-and-swell and boudinage). Finally, in some of the less-deformed veins a regular fine banding perpendicular to the vein walls, and generally vertical or steeply dipping, exists and is defined by colour variation in the vein quartz (alternating bands of grey and white). An idealized synoptic diagram of all the features mentioned above is given as Figure 5, and their microstructures are described below.

VEIN MICROSTRUCTURES

The features of the bedding-concordant veins which have been examined are: vein-wall rock contacts; intercalated quartz and slate layers and fragments and their mutual contacts; the closely-spaced phyllosilicate lamination; the jagged planar structures; the 'columnar' structure; and the fine colour banding. These will be described in turn.

(i) vein-wall rock contacts: vein contacts are sharp, and while mesoscopically planar, are irregular at the microscopic scale (Fig. 6). The quartz veins locally truncate the slaty cleavage of the host rocks (Fig. 6), and where truncated, the cleavage generally does not bend towards parallelism with the vein.

(ii) intercalated slate fragments and layers: the contacts between these and the vein material are again sharp, irregular at the microscopic scale, and locally truncate the slaty cleavage in the layers and fragments. These contacts are identical in every respect to the vein-wall rock contacts. Very commonly, the margins of slate fragments and layers towards the wall rock are shaped identically to irregularities in the vein-wall rock contact. If intervening vein quartz were removed, these fragments could be fitted into the vein walls, and the slaty cleavage in wall rock and fragment would then be coincident.

Intercalated slate layers can have extreme length/width ratios (several hundreds to one), but invariably terminate within

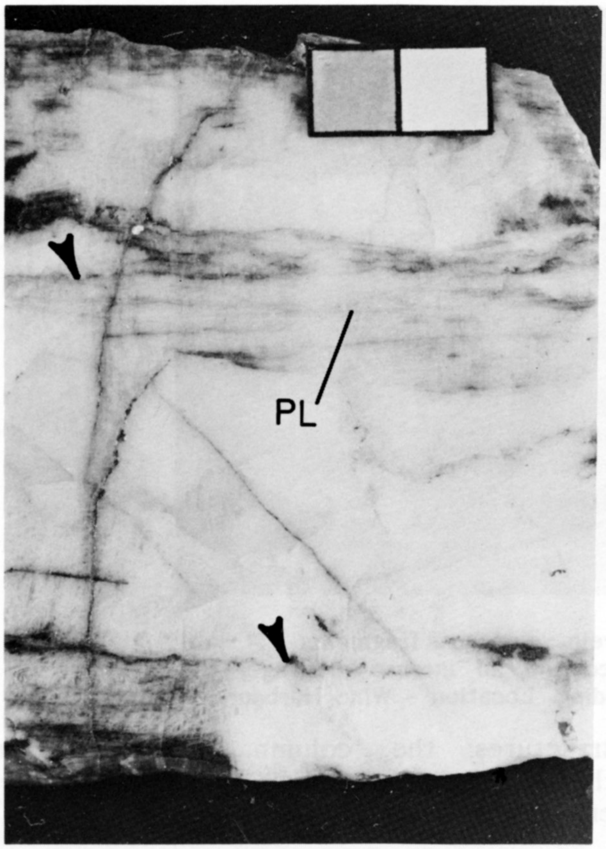

Fig. 3 - Sawn face of sample, phyllosilicate laminae indicated (PL). Note jagged structures (arrowed) which truncate phyllosilicate laminae. Sample from Harrigan Cove. Scale = 2 cm.

the vein at one or usually both ends (Fig. 2).

(iii) phyllosilicate lamination: the phyllosilicate lamination is composed of very narrow (3-20 μm) laminae of white mica and/or chlorite, separated by 20-100 μm or so of quartz, though this separation is irregular (Fig. 7). The laminae are commonly short and totally enclosed in several quartz grains, though zones of laminae extend perpendicular or oblique to the vein walls for considerable distances (Figs. 4 and 5). Individual phyllosilicate grains in the laminae are commonly parallel to the length of the laminae, less commonly oblique to the laminae. Individual phyllosilicates in the laminae are generally of the same size as wall rock phyllosilicates, though larger white mica grains are observed locally. The quartz separating laminae is of the same crystallographic orientation (ie. a single grain) across considerable widths of individual veins (at least 5 cm measured in one case). Detailed information about the quartz crystallographic preferred orientations will be reported elsewhere.

(iv) jagged planar structure: while mesoscopically planar, these possess considerable microscopic relief (Fig. 8). They are generally 10-40 μm wide, though this is variable. These structures consist of phyllosilicate grains (roughly parallel to the length of the structure), fine oxide grains, and rarely fine feldspar grains. They commonly truncate the phyllosilicate lamination, and individual laminae can be correlated across the 'peaks' and 'valleys' of the jagged structure (Fig. 8). This has been called 'cross-lamination' by other workers, but these structures are clearly tectonic stylolites.

(v) 'columnar' structure: microscopically, the 'columnar' structure is observed to be due to elongate single quartz grains, some of which possess zones of phyllosilicate laminae (Figs. 4 and 5). Single grains at least 5 cm long and 1.5 cm wide have been observed. Rarely, these individual elongate grains have the form of quartz crystals with well-developed prism faces (see Figure 1-4b of Henderson 1983b). The morphology of these single quartz grains is quite unlike that of columnar geyserite (see Walter 1976) with which they have been compared (Haynes 1983), and is discussed in more detail below.

(vi) colour banding: this enigmatic structure seems to be due to alternating zones of fluid inclusion-rich versus fluid inclusion-poor quartz. The effect is very subtle at the microscopic scale.

VEIN ORIGIN

As mentioned previously, two main hypotheses for the origin of the bedding-concordant auriferous quartz veins of Nova Scotia are currently favoured. These will be briefly reviewed, and then evaluated in terms of the structural evidence presented above.

Hypothesis 1: Haynes (1983) has proposed that the bedding-concordant quartz veins are pretectonic, formed on the ocean floor around submarine hot springs. In this hypothesis, hot hydrothermal solutions have precipitated an apron of siliceous sinter (geyserite) around the discharging hot-spring vent (Walter 1976). The fine phyllosilicate laminations are thought to represent sedimentation of hydrothermal phyllosilicates from the discharging fluid, and the intercalated slate layers represent either intermittant pelagic sedimentation or intermittant small, fine-grained turbidity flows. Haynes (1983) correlates the 'columnar' structure which is preserved in some veins with the columnar form of geyserite.

Hypothesis 2: Henderson (1983a) and Mawer (1985), among others, have proposed that the bedding-concordant quartz veins are syntectonic, and formed by the infilling of hydraulic fractures generated essentially parallel to bedding. The vein minerals precipitated from the fracturing aqueous solutions. The phyllosilicate laminations in this hypothesis represent successive crack-seal increments (Ramsay 1980), and the intercalated slate fragments and layers represent pieces of the vein walls separated from the host by fractures which diverge slightly from the vein wall into the wall rock, leaving a thin sheet of wall rock attached to the vein. The 'columnar' structure preserved in some veins is due to growth of favourably oriented quartz grains, either from the vein or from the wall rock, into the open hydraulic fracture (for example, Cox and Etheridge 1983, Figure 9).

At this point, it is worthwhile to examine the work of Walter (1976), cited by Haynes (1983) in support of his hypothesis of a geyserite origin for the bedding-concordant quartz veins. Several pertinent facts emerge. The first is that geyserite is an opaline form of silica (Walter 1976, p. 87), that is, composed of cryptocrystalline units of silica of different

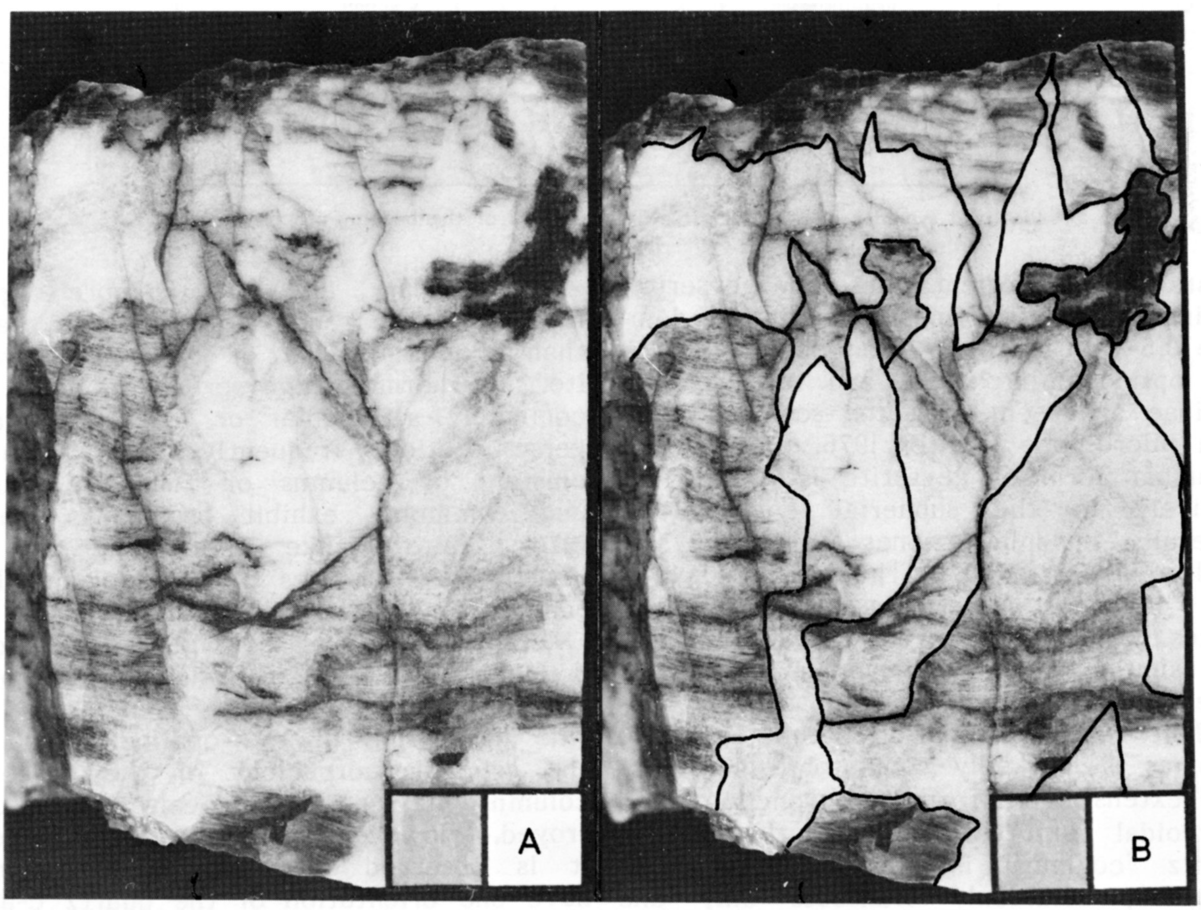

Fig. 4 - 'Columnar' structure. Columns outlined in Figure 4b. Sample from Harrigan Cove. Scale = 2cm.

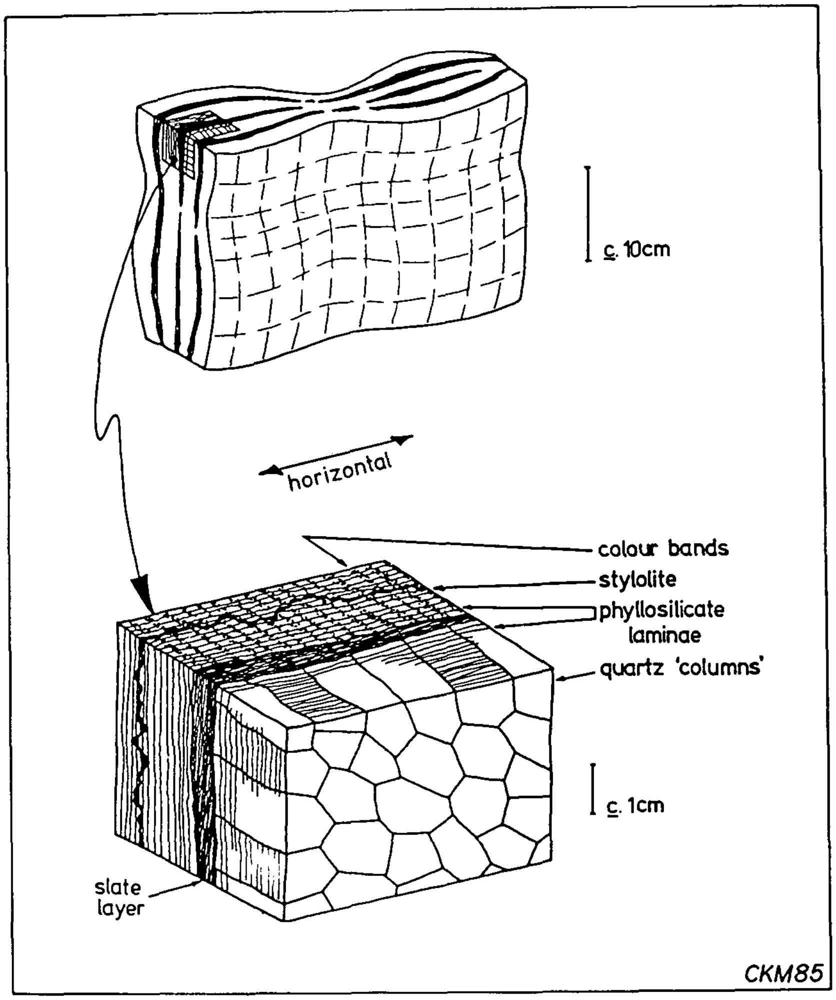

Fig. 5 - Idealized synoptic diagram of structural features of the bedding-concordant quartz veins.

crystallographic orientations. The geyserite lamination is very fine, consisting of laminae 0.5-4.0 μm thick when observed using the optical microscope, and even thinner laminae are seen using the scanning electron microscope (Walter 1976, p. 103). The columnar form of geyserite is formed exclusively in the subaerial environment, generally in splash zones around geysers (Walter 1976, p. 107). The morphology of the columnar geyserites (Walter 1976, Plates 6, 10, 11, 21 to 23, 28, 30 to 33) is not similar to the 'columnar' structures observed in Meguma Terrane bedding-concordant veins. Lamination within geyserite columns is markedly undulatory and laterally extensive or forms a strongly curved botryoidal texture. The lamination in the quartz 'columns' is generally planar or irregular, commonly transects only one 'column' and is abruptly truncated at the grain boundary, and is both more regular in appearance and more widely spaced than the lamination of columnar geyserite. Furthermore, geyserite columns are commonly subcircular or lobate in transverse section, frequently form radiating clusters of columns or rounded mounds, and commonly exhibit branching (Walter 1976), quite unlike the habit of the 'columnar' structures of the Meguma Terrane veins.

Metamorphism of a geyserite would doubtless cause significant grain growth and coarsening of quartz, and thus the fine lamination of the opaline silica and the original morphology of the geyserite columns may perhaps be altered or destroyed. However, in less-deformed veins it is observed that individual 'columns' have one orientation of the quartz c-axis, that is, they are effectively single quartz

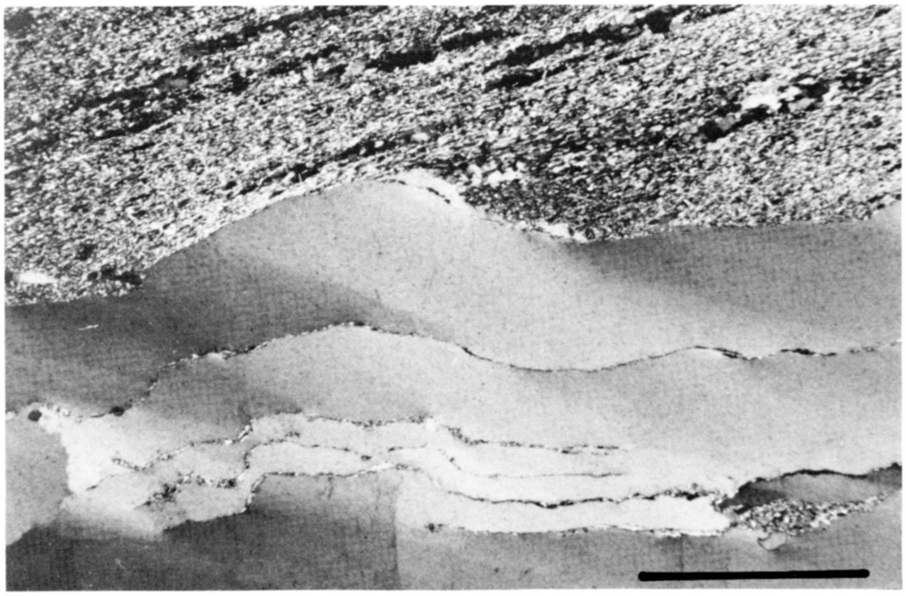

Fig. 6 - Vein-wall rock contact. Note truncation of slaty cleavage in wall rock, and phyllosilicate laminae with similar topography to vein contact. Sample from Harrigan Cove. Scale bar = 1 mm.

grains (see above, also Henderson and Henderson 1984, Mawer 1985). It is extremely difficult to imagine a mechanism by which a column of originally opaline silica, with each tiny unit of silica in a different crystallographic orientation (Frondel 1962, p. 288), could be recrystallized to yield one grain of quartz. Studies of natural and experimental dynamic and annealing recrystallization of very fine grained siliceous material (for example, Tullis **et al.** 1973, Masuda and Fujimura 1981, Joesten 1983) invariably show that such material recrystallizes to a polycrystalline aggregate. Further, it would appear to be difficult to reconcile the subaerial environment of formation of columnar geyserites with the deep-sea environment of deposition of their host greywackes and slates, if both were formed contemporaneously as Haynes' (1983) hypothesis demands.

As described previously, the intercalated slate layers within veins are not laterally continuous. In hand sample or thin section, it is commonly observed that many intercalated slate layers and fragments could be fitted back into identically-shaped irregularities in the vein walls if intervening quartz was removed. Both the slate of the vein walls and in intercalated fragments and layers possesses a slaty cleavage. The quartz veins locally truncate this cleavage both along vein walls and intercalated slate fragments and layers, as described previously. If slate fragments were fitted into vein walls, this cleavage would be continuous across the wall-fragment boundary. Further, the slaty cleavage is generally abruptly truncated by the quartz veins, rather than bending towards parallelism with them. Both of these facts indicate that the slaty cleavage was present before the vein developed.

The observed phyllosilicate lamination is very similar in appearance to crack-seal phenomena described elsewhere (Ramsay 1980, Cox and Etheridge 1983, van der Pluijm 1984), and is held to have developed by this mechanism. Successive periodic hydraulic fractures occur along vein walls and either separate a layer of phyllosilicates from the wall rock (for those laminae with parallel phyllosilicate grains), or allow syntaxial overgrowth on wall rock phyllosilicates (for those laminae with oblique phyllosilicate grains). Hydraulic fractures which deviate slightly from vein walls into the wall rock separate slate layers and fragments, and cause these slate pieces to be intercalated into the developing vein. The 'columnar' structure is a direct consequence of the crack-seal

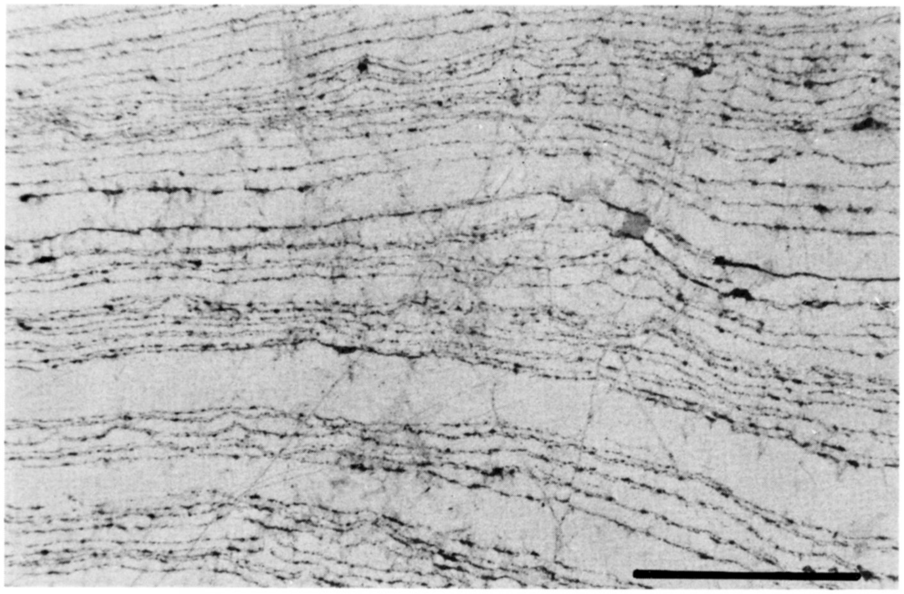

Fig. 7 - Phyllosilicate lamination. Sample from Renfrew. Scale bar = 1 mm.

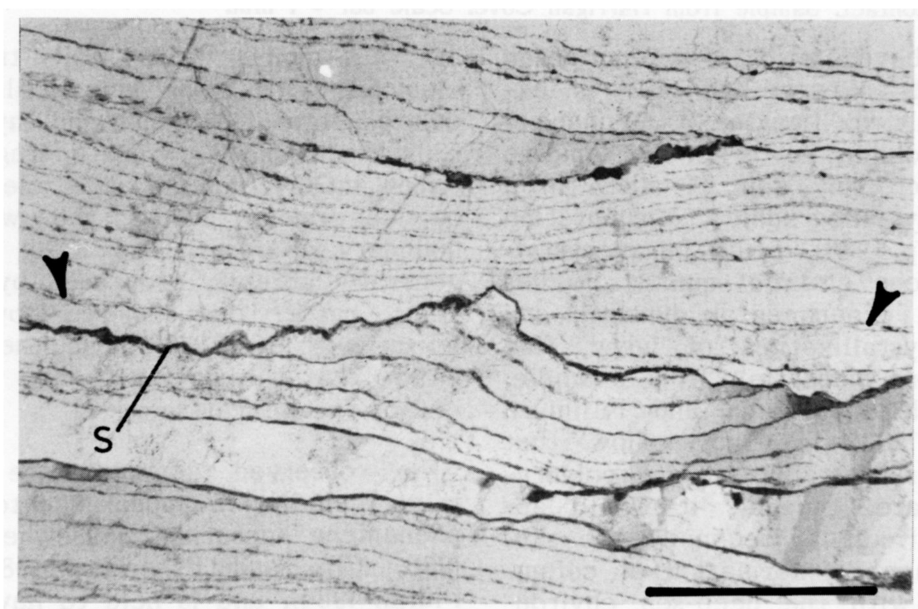

Fig. 8 - Jagged planar structure (stylolite, marked S). Note that this structure truncates the phyllosilicate lamination (one truncated lamina is arrowed). Sample from Renfrew. Scale bar = 1 mm.

process (see Ramsay 1980, Cox and Etheridge 1983).

Conclusions

1. Bedding-concordant quartz veins occurring in Meguma Terrane rocks of Nova Scotia are syntectonic. In every example studied so far, the veins locally truncate both bedding and a tectonic foliation (slaty cleavage). This is especially obvious at the microscopic scale.

2. The veins possess a complex and characteristic assemblage of mesoscopic and microscopic structures. Structures consistent with a vein origin by periodic hydraulic fracturing and fracture healing abound (crack-seal inclusion bands and trails, intercalated wall-rock fragments,

elongate quartz crystals at a high angle to vein walls), and are overprinted by later tectonic phenomena (tectonic stylolites, pinch-and-swell structure). These features are not consistent with a pretectonic, submarine hot spring apron origin for the veins.

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