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Distribution and Localization of Gold in Meguma Group Rocks, Nova Scotia: Implications of Metal Distribution Patterns in Quartz Veins and Host Rocks on Mineralization Processes at Harrigan Cove, Halifax County

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Article abstract

The contents of Au, As, Sb and W in metagreywacke, slate and quartz veins from Harrigan Cove, Halifax County, N.S. were determined by neutron activation analysis. The gold-bearing veins in the Goldenville Formation, the lower sandy flysch member of the Cambro-Lower Ordovician Meguma Group of eastern Nova Scotia. The Harrigan Cove metagreywacke and slate are strongly enriched in arsenic (as arsenopyrite) and weakly enhanced in gold relative to similar lithologies in barren Meguma terranes. Creywacke is the main sink for arsenic while gold occurs in highest concentration in greywacke and slate, but not in the quartz veins- Anomalous gold values occur with the same frequency in greywacke, slate and quartz veins, but anomalous quartz vein samples are much richer in gold than anomalous host rock samples.

It is suggested that the metal distributions support a polygenetic origin for the mineralization, whereby early arsenic- and sulphur-bearing fluids introduce arsenopyrite and sulphides, mainly into greywacke. Gold is concentrated by these minerals and later mobilized along with large quantities of silica early in the history of deformation through pressure solution processes which generate a spaced cleavage. These silicic fluids and their metals are then injected by hydraulic fracture, mainly into slate, to form the gold-bearing bedding-parallel quartz veins.

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The contents of Au, As, Sb and W in metagreywacke, slate and quartz veins from Harrigan Cove, Halifax County, N.S. were determined by neutron activation analysis. The gold-bearing veins in the Goldenville Formation, the lower sandy flysch member of the Cambro-Lower Ordovician Meguma Group of eastern Nova Scotia. The Harrigan Cove metagreywacke and slate are strongly enriched in arsenic (as arsenopyrite) and weakly enhanced in gold relative to similar lithologies in barren Meguma terranes. Greywacke is the main sink for arsenic while gold occurs in highest concentration in greywacke and slate, but not in the quartz veins. Anomalous gold values occur with the same frequency in greywacke, slate and quartz veins, but anomalous quartz vein samples are much richer in gold than anomalous host rock samples.

It is suggested that the metal distributions support a polygenetic origin for the mineralization, whereby early arsenic- and sulphur-bearing fluids introduce arsenopyrite and sulphides, mainly into greywacke. Gold is concentrated by these minerals and later mobilized along with large quantities of silica early in the history of deformation through pressure solution processes which generate a spaced cleavage. These silicic fluids and their metals are then injected by hydraulic fracture, mainly into slate, to form the gold-bearing bedding-parallel quartz veins.

La teneur de Au, As, Sb et W dans les metagrauwackes, l'ardoise, et les veines de quartz de Harrington Cove, conté de Halifax, N.E., a été déterminée par analyse d'activation de neutrons. Les veines de quartz ici contenant de l'or, sont typiques des veines de quartz de genre turbidite de la formation de Goldenville, le membre inferieur sabloneu de flysch du Groupe Meguma Cambro-Bas Ordovicien de l'est de la Nouvelle Ecosse. Le meta-grauwacke et l'ardoise de Harrigan Cove sont fortement enrichis d'arsenic, (en temps qu'arsenopyrite), et sont faiblement relevés en teneur d'or par rapport aux lithologies comparable des terrains stérile Meguma. Le grauwacke est l'entonoir principal pour l'arsenic, alors que l'or se trouve en concentration plus élevé dans les veines de quartz. L'or et l'arsenic sont en corrélation dans le grauwacke et l'ardoise, mais pas dans les veines de quartz. Des valeurs d'or anormales se trouvent avec la même fréquence dans le grauwacke, l'ardoise et les veines de quartz, mais les échantillons de quartz sont nettement plus riches en or que les échantillons des roches-hôtes.

Il a été suggéré que la distribution de métaux soutient l'idéee d'une origine polygénétique pour la minéralisation, tandis que les premiers fluides contenant de l'arsenic et du souffre introduisent de l'arsenopyrite et des sulfides, surtout dans le grauwacke. L'or est concentré par ces minéraux et est plus tard mobilisé avec de grandes quantitées de silice, tôt dans l'histoire de la déformation, par des processus de solutions de pression, qui engendrent un clivage espacé. Ces fluides silicieux et leurs métaux sont alors injectés, au moyen de fractures hydrauliques, surtout dans l'ardoise, pour former les veines de quartz contenat de l'or, au litage paralèlle.

INTRODUCTION

Recent studies of auriferous quartz veins in turbidites of the Meguma Group, Nova Scotia have provided useful new insight into the mechanisms and timing of vein emplacement (Keppie, 1976; Graves and Zentilli, 1982; Henderson, 1983a). The question of the source of vein fluids, and their

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metals, has given rise to a variety of models whose diversity indicates that vein genesis is not yet well understood. The following concepts provide examples of recent thinking. Haynes (1983) proposed a model by which some of the auriferous veins were considered to have formed in submarine hydrothermal-vent hot spring systems which tap sub-Meguma basement through faults. The basement was suggested as the source of gold. Kretschmar (1983) argued that the stratiform veins are syngenetic chemical sediments precipitated from brines in the depositional basin. Other models involve a local derivation of the vein silica and link vein formation with deformation, calling on pressure solution of quartz accompanying the development of spaced cleavage as a means of liberating silica (Clifford et al., 1983; Fueten et al., this volume). Opinions as to the source of gold and other metals are without strong consensus.

Studies which document the distribution of gold and associated metals in the various gold districts of the Meguma terrane should help constrain genetic thinking. Smith (1983a, b), for example, provided a detailed survey of the gold distribution in quartz veins and host rocks of the Cochrane Hill deposit, localized in amphibolite grade rocks. The present study was carried out on the Harrigan Cove mineralization, which is hosted in greenschist facies rocks. Good bedrock exposure is provided here by trenching and overburden stripping. Gold and associated metals, including arsenic, antimony and tungsten, were determined in metagreywacke and slate host rocks as well as in quartz veins. The metal distributions are considered with regard to a possible source of metals in local host rocks or in quartz-vein fluids. The evaluation is based primarily on gold and arsenic patterns. Little independent insight was gained from antimony values as the metal is correlated so strongly with arsenic. Tungsten was determined on a limited suite of samples only and the geochemical implications of the tungsten data are not pursued here in any detail.

GEOLOGICAL SETTING OF THE HARRIGAN COVE GOLD MINERALIZATION

The Harrigan Cove gold district is located about 100 km east of Halifax in the southeast corner of Halifax County. Trenches and stripping expose auriferous quartz veins 400 to 700 m north of Harrigan Cove post-office just off Highway No. 7 (Ecum Secum map, 11D/16). The bedrock is greywacke and slate of the Goldenville Formation, the lower member of the Cambro-Lower Ordovician Meguma Group. Gold production from the Harrigan Cove district from 1899 to 1916 was about 225 kg, somewhat less than 1% of the total production from Nova Scotia prior to 1927 according to data tabulated in Appendix 1 of Malcolm (1976). Quartz veins were the principal source of gold although some slate was milled.

The main structural elements and the distribution of quartz veins as mapped by E.R. Faribault (1906) are reproduced in Figure 1. All productive beings lay in the south limb of the South Anticline and follow the bedding. Trenches and sample locations are sketched on Figure 1. Some of the important quartz veins shown on Faribault's 1906 map are probably exposed in the trenches. These include the South Whidden and Bishop veins in the most northerly trench, the McIlrich and Galena veins in the central area and possibly the South vein in the southern trench.

Recent studies of the Harrigan Cove gold district include those of Anderle (1974), Kretschmar (1983) and Henderson (1983b). Comment below is based mainly on the latter two studies and mapping carried out by the present authors, principally F. Fueten (Fig. 2). The principal host rocks are greywacke and slate, the A and E divisions, respectively, of Bouma turbidite units. The greywackes occasionally include C division rocks toward their

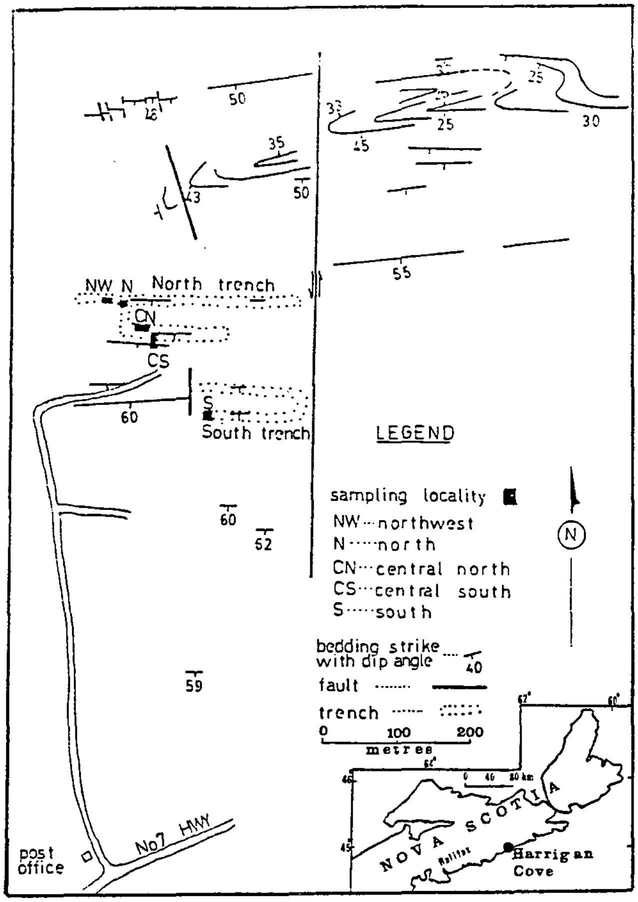

Figure 1 - Geological sketch map of Harrigan Cove showing the principal structural elements after Faribault (1906). Trenches and sample locations for this study are indicated.

stratigraphic tops. Evidence supporting the interpretation of the Meguma as a turbidite sequence deposited in one or more submarine fans is documented by Schenk (1970). At the mapped localities bedding dips 60 to 85° degrees south and strikes approximately 090°. The bedding-cleavage angle is generally less than 25° in both greywacke and slate. Most quartz veins and all those thicker than 5 cm are essentially bedding-parallel and either hosted entirely within E division slates or localized along the contacts between E divisions and the base of the overlying greywacke beds. Other veins include rare, thin (1 to 5 cm), discordant quartz veins which usually originate in thicker, bedding-parallel veins. Arsenopyrite occurs in all rock types, but is most common in greywacke beds as euhedral crystals up to 5 mm long and is often concentrated toward the coarser grained base of the bed. Pyrrhotite and pyrite occur in all lithologies, but are much less common than arsenopyrite.

Five localities (Fig. 2) representing a stratigraphic sequence about 120 m thick were mapped and sampled. For each locality (Fig. 3a, 3b, 4) the Bouma units are numbered sequentially, with the stratigraphically lowest unit designated as 1. Lithological divisions in Bouma units are identified by A for greywacke, B, C or D for slaty greywacke and E for slate. Quartz veins are indicated by Q. Where more than one sample was collected from a specific lithology they were differentiated numerically, using 1 for the stratigraphically lowest sample.

Geology of Sampled Localities

North Trench. The North trench exposes several prominent bedding-parallel quartz veins, each 20 to 30 cm thick and their sedimentary host rocks. Two areas were sampled in detail. One, designated the Northwest locality (Fig. 3a), consists of three Bouma units of approximately 4.5 m total thickness. Greywacke and slaty greywacke are dominant and several beds contain euhedral arsenopyrite crystals. A bedding-parallel quartz vein, 25 cm thick, possibly the South Whidden vein (Faribault, 1906), occurs in the basal Bouma unit. Euhedral arsenopyrite occurs sparingly in this vein at quartz vein-slate contacts. Massive nodular arsenopyrite (Sample NW1Q2a) was found where local folding apparently resulted in brecciation of the vein. The nodular arsenopyrite is highly anomalous in gold (270 ppb). The slate in contact with this vein and a thin parallel vein contains a few euhedral crystals of arsenopyrite, and is also anomalous in gold (15 to 50 ppb). Nodular arsenopyrite was observed in only one other locality where it is also anomalous in gold.

A second area in the North trench, designated the North locality (Fig.

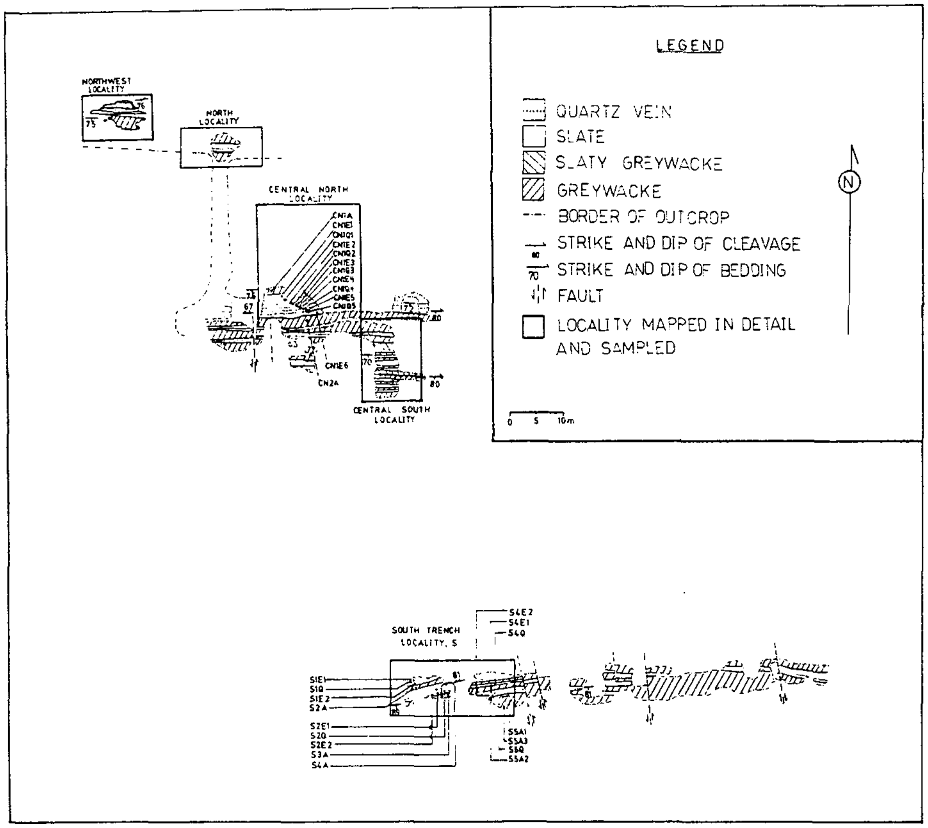

Figure 2. Harrigan Cove area, Halifax County, N.S., showing geology of some of the stripped and trenched exposures and indicating the areas sampled in detail for this study. Geology by F. Fueten.

3b), was also sampled. Although stratigraphic continuity between the North and Northwest localities is uncertain due to overburden cover, the upper greywacke of the Northwest locality, NW3A, is probably equivalent to the lowest greywacke in the North locality. This latter unit is therefore designated N3A. The North locality exposes two Bouma units, mainly of greywacke, that total 3.5 m in thickness. The lower Bouma unit includes a slate member which contains a bedding-parallel quartz vein that is 50 cm thick and is probably the productive Bishop vein (Faribault, 1906).

Central North (CN) locality in the North trench (Fig. 2) consists of a single Bouma unit of basal A division greywacke overlain by about 4.5 m of C, D and E division slate and slaty siltstone. It is unusually thick in comparison with other Harrigan Cove Bouma units. Five stratabound quartz veins are hosted in the slate unit.

Central South (S) locality in the North trench exposes a stratigraphic sequence approximately 13.2 m thick consisting of twelve Bouma units most of which are represented by A, E and occasionally C divisions (Fig. 4). The overall lithic proportion of greywacke:slate:quartz vein is 7:2.4:1. The quartz veins are predominantly bedding-parallel and average 15 cm in thickness. A few thin discordant quartz veins, generally less than 5 cm thick, cut from one to three Bouma units and appear to originate in the bedding-parallel veins. Many of the greywacke beds contain euhedral arsenopyrite crystals up to 25 cm long. Arsenopyrite is much less common in the slate beds and quartz veins. Pyrite and pyrrhotite occur occasionally in quartz veins.

<u>South Trench</u> (S). The west end of the South trench (Fig. 2) contains a

relatively undisturbed, continuous stratigraphic succession with several quartz veins. A sampled sequence approximately 10 m thick and containing five Bouma units consists of greywacke (A division) and slate to silty slate (C, D and E divisions). Quartz veins are bedding-parallel and occur near the top of Bouma units, commonly within slates. One particularly thick A division member, S5, represents several amalgamated beds.

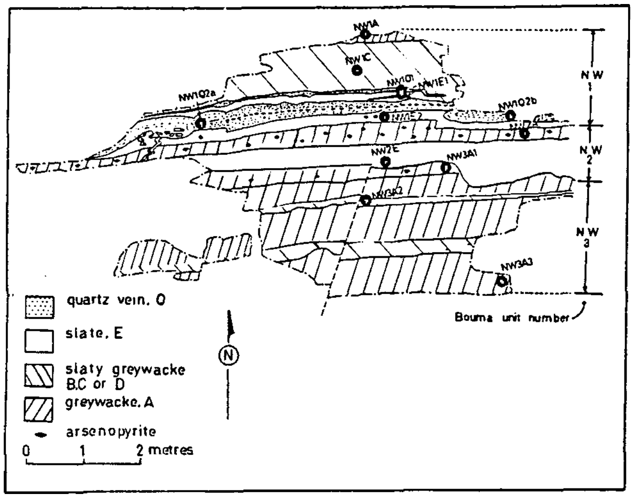

Figure 3a. Geology and sample locations in the Northwest (NW) locality in the North trench showing three Bouma units. Unit 3 ccconsists of amalgamated beds. Beds face and dip south at an average of 75°. Slaty cleavage is essentially parallel to bedding. The main quartz vein NW1Q2 is bedding-parallel. Geology by J.H. Crocket.

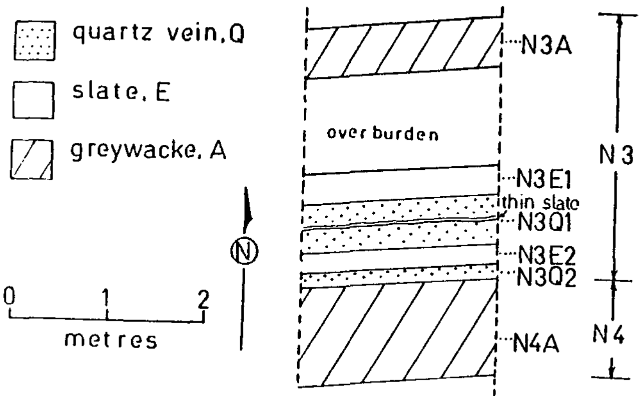

Figure 3b. Representative section across the North (N) locality in the North trench showing two Bouma units. Beds face south, strike 085° and dip 75° south. Quartz veins are bedding-parallel.

METHODS AND PROCEDURES

Field Sampling

Samples were collected either by hammer or by drilling with a portable diamond-bit unit which took a core 2.5 cm in diameter and up to 15 cm long. Drilling permitted precise sample location so that thin E units or the base, middle and top of specific beds could be sampled.

In the Central South locality Bouma units 1 to 8 were fractured and broken across strike by blasting nineteen holes charged sufficiently to break but not to scatter the rock fragments. Thicker greywacke beds could thus be sampled by taking several pieces across the full width of the bed. Quartz veins were usually sampled by collecting single pieces representing the full width of the vein. Samples of approximately 2 kg total weight were taken from each bed.

Analytical Procedures

Samples were broken in a jaw crusher to approximately 0.5 cm pieces and then pulverized in a ceramic disk grinder to a particle size of 1 mm or less. A split of 0.5 kg was then powdered in a ceramic disk grinder to pass a minus 200 mesh screen. From the minus 200 mesh powder an aliquot of 0.5 g was taken for analysis.

Instrumental epithermal neutron activation was employed for Au, As, Sb and W analyses, using a rotating cadmium shielded irradiation site in the McMaster Nuclear Reactor. Samples were irradiated in batches of fourteen plus two standards for 1 megawatt-hour (1×10^{13} neutrons/cm^2/sec) and allowed to decay for approximately 24 hours prior to counting As and W. Au and Sb were counted after further decay of 72 hours. Gamma ray spectra were taken on a coaxial intrinsic germanium detector with a resolution of 1.7 Kev and a

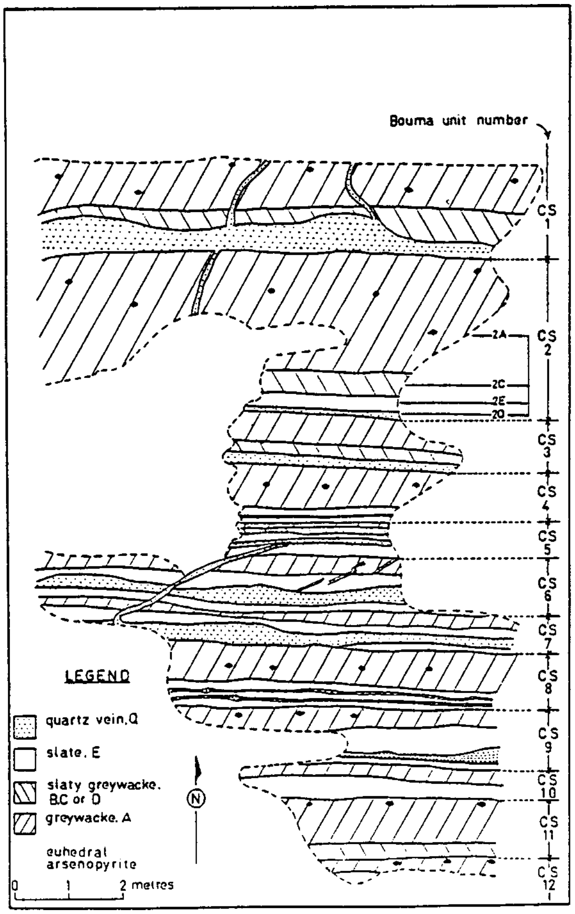

Figure 4. Geology of the Central South locality (CS) showing twelve Bouma units (e.g. CS1 -- Bouma unit 1, Central South locality). Beds face south with an average dip of 70° south. Quartz veins are mainly bedding-parallel. Some minor discordant veins are 1 to 5 cm wide. Their width on the figure is exaggerated for clarity. Geology by U. Kretschmar (1983).

peak-to-background ratio of 15:1 at 0.662 Mev. The essential analytical parameters are:

Element	Nuclide Counted	Half-Life Hours	γ-ray Energy, Kev
Arsenic	^{96}As	26.3	559
Tungsten	^{187}W	23.9	686
Gold	^{198}Au	64.7	412
Antimony	^{122}Sb	65.3	564

Standards were prepared by adding a weighed amount of weakly acidic solutions of known metal content to high purity silica powder and evaporating to dryness. Spec-Pure grade metals or oxides were used to prepare the standard metal solutions. The sensitivity of the analytical procedure is: As, 1 ppm; W, 0.1 ppm; Au, 1 ppb and Sb, 0.1 ppm.

Total carbon was determined with a LECO gas analyser which measured CO$_2$ adsorption in the infrared. This method yields total carbon.

RESULTS

The contents of gold, arsenic, antimony, tungsten and total carbon are presented in Table 1 with averages in Table 2. The distribution of gold in Harrigan Cove greywacke, slate and quartz veins is shown in histograms in Figure 5 which illustrate the pronounced positive skewness of the metal distribution. The main purpose of the averages (Table 2) is to recognize significant differences in metal content from one locality to another, but it is apparent from Figure 5 that a few metal-rich samples in each

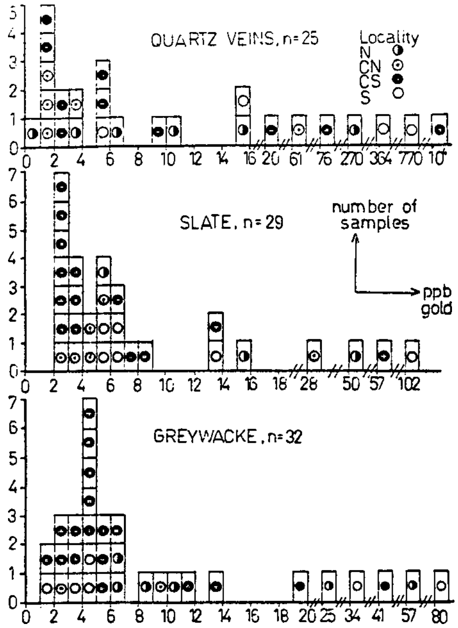

Figure 5. Histograms showing distribution of gold at Harrigan Cove in (a) greywackes, (b) slates and (c) quartz veins.

Table 1.

GOLD, ARSENIC, ANTIMONY, TUNGSTEN AND TOTAL CARBON AT HARRIGAN COVE

(a) Northwest locality (NW)

Sample	Au ppb	As ppm	Sb ppm	W ppm	CO_2 wt. %
NW1A	10	650	4.8	5.1	0.33
NW2A	57	13,900	30	-	0.23
*NW3A	8.9	1.380	8.6	4.9	0.38
NW1C	6.7	230	2.9	9.3	0.24
NW1E1	50	6,120	34	31	0.32
NW1E2	15	2,215	15	18	0.15
NW1Q1	15	540	4.1	4.1	0.15
**NW1Q2a	10	1,180	7.5	22	-
**NW1Q2a	270	35,000	84	-	-
**NW1Q2b	6.6	87	0.97	2.4	0.13

* A composite of samples NW3A1, NW3A2 and NW3A3

** NW1Q2 contains nodular arsenopyrite. Subsample 2a is an arsenopyrite-poor fraction, and subsample 2b is an arsenopyrite-rich subsample.

(b) North locality (N)

Sample	Au ppb	As ppm	Sb ppm	W ppm	CO_2 wt. %
N4A1	25	8,060	31	4.2	0.17
N4A2	6.9	960	4.1	3.2	0.17
N3E2	5.4	135	2.4	13	0.30
N3Q1	0.88	5.5	0.27	0.07	0.09
N3Q2	3.2	37	0.73	4.4	0.15

(c) Central locality (CW)

Sample	Au ppb	As ppm	Sb ppm	CO_2 wt. %
CN1A	2.7	320	2.8	0.19
CN2A	9.4	1,570	12	0.19
CN1E1	5.6	465	4.7	0.30
CN1E2	4.2	115	1.9	0.34
CN1E3	28	3,060	22	0.25
CN1E4	3.6	190	2.3	0.28
CN1E5	4.0	270	3.7	0.22
CN1E6	2.5	100	1.5	1.51
CN1Q1	1.8	110	1.5	0.15
CN1Q2	61	150	1.5	0.11
CN1Q3	3.7	6.0	0.75	0.15
CN1Q4	1.3	440	4.7	0.16
CN1Q5	1.5	2.6	0.32	0.13

TABLE 1 cont'd

(d) the Central South locality (CS)

Sample	Au ppb	As ppm	Sb ppm	W ppm	CO_2 wt. %
CS1A	13	4,170	13	15	0.21
CS2A	5.5	2,030	16	10	1.16
CS3A	5.3	1,780	6.4	10	0.16
CS4A	3.0	450	3.4	8.3	0.67
CS5A	11	2,300	8.0	13	0.21
CS6A	4.8	1,270	4.0	11	0.28
CS7A	4.1	1,260	4.2	15	0.21
CS8A	4.2	830	2.7	12	0.31
CS9A	19	2,790	16	-	0.59
CS10A	3.5	31	1.0	-	0.21
CS11A	4.9	90	0.89	-	0.29
CS12A	41	14,400	45	-	0.16
CS1C	6.8	3,650	12	25	0.27
CS2C	2.5	41	0.60	5.8	0.27
CS3C	1.7	39	0.85	12	0.20
CS5C	2.0	41	0.77	12	0.175
CS6C	5.6	160	1.9	16	0.28
CS11C	4.8	2,020	11	-	0.195
CS2E	59	68	1.0	10	0.28
CS4E	3.5	63	0.94	11	0.31
CS5E1	2.6	510	3.4	23	0.41
CS5E2	2.7	580	3.0	13	0.33
CS6E1	2.8	50	0.82	14	0.33
CS7E1	7.2	125	6.5	-	0.39
CS7E2	8.6	270	3.8	-	0.41
CS8E1	2.4	47	0.98	14	0.30
CS8E2	3.7	65	0.96	16	0.29
CS9E1	6.6	36	1.3	-	0.31
CS9E2	3.8	61	1.4	-	0.39
CS10E	2.6	38	1.1	-	0.29
CS11E2	13	1,330	7.8	-	0.29
CS1Q	76	10	0.50	0.29	0.09
CS2Q	2.9	18	0.40	7.2	0.11
CS3Q	20	1,445	9.7	10	0.14
CS4Q	5.7	410	1.6	6.8	0.13
CS5Q	9.1	400	2.7	11	0.13
CS6Q	2.0	180	1.2	16	0.10
CS7Q	1.5	5.5	0.37	14	0.10
CS8Q1	1.3	15	0.52	21	0.13
CS8Q2	10,000	90,000	190	53	0.12
CS9Q	5.8	5.3	0.50	-	0.13

(e) South Trench locality (S)

Sample	Au ppb	As ppm	Sb ppm	CO_2 wt. %
S2A	4.2	17	0.73	1.15
S3A	1.9	30	0.73	0.11
S4A	34	16	1.1	0.68
S5A1	3.4	22	0.48	0.18
S5A2	4.5	14	0.42	0.80
S5A3	80	25	0.82	0.14
S1E1	102	11,600	63	0.24
S1E2	5.1	165	1.7	0.24
S2E1	6.3	74	1.2	0.22
S2E2	5.7	47	1.5	0.24
S4E1	13	128	1.4	0.23
S4E2	6.4	17	0.93	0.21
S1Q	364	52	1.5	0.14
S2Q	15	17	1.1	0.12
S4Q	5.4	96	1.2	0.09
S5Q	770	11	0.31	0.11

Table 2.

AVERAGE METAL AND CO_2 CONTENTS AT HARRIGAN COVE

(a) by locality and lithology

Locality	Average Metal and CO_2 Contents in A, E and Q Divisions														
	Au, ppb			As, ppm			Sb, ppm			W, ppm			CO_2 wt.%		
	A	E	Q	A	E	Q	A	E	Q	A	E	Q	A	E	A
N+NW	19	24	6.4	4203	2823	167	14	17	1.5	5.3	21	2.8	.30	.26	.13
CN	6.1	8.0	14	945	228	142	7.4	2.8	1.8	-	-	-	.19	.28	.14
CS	6.0	4.8	14	1350	152	277	6.0	1.9	1.9	12	13	11	.33	.33	.12
S	21	23	289	21	86	44	0.71	1.0	1.0	-	-	-	.51	.23	.12

(b) by lithology for all samples

	Au, ppb			As, ppm			Sb, ppm			W, ppm			CO_2 wt.%		
Lithology	A	E	Q	A	E	Q	A	E	Q	A	E	Q	A	E	Q
Average	8.7	8.0	62	972	549	184	4.9	3.5	1.7	9.8	14.8	8.1	.35	.34	.12
No Samples	30	27	22	27	30	22	29	27	22	17	10	12	30	31	23

lithological population will strongly bias total population arithmetic means. The rigorous choice of a better statistical parameter to estimate the population mean is difficult as the metal populations do not fit a simple distribution (such as normal or lognormal) when tested by plotting on probability paper. Arbitrarily, the averages used in Table 2 are the arithmetic means for the data within an $\bar{x} \pm 2\sigma$ interval. This method tends to exclude one, or occasionally two, high value samples from the population averages.

Correlation plots for gold vs arsenic are presented in Figure 6 and a matrix for all interelement correlations is given in Table 4.

Gold production at Harrigan Cove from 1899 to 1916 was approximately 225 kg gold from 13, 052 tons of ore (Malcolm, Appendix 1, 1976) equivalent to an average grade of 19 ppm gold. The average gold contents of Harrigan Cove quartz veins, slates and greywackes are relatively low but are anomalous in a geochemical sense when compared with Meguma rocks from unmineralized districts or with literature averages for comparable lithologies. A similar comparison for arsenic shows the metal is also strongly anomalous in the Harrigan Cove rocks, in fact far more so than gold. The data on which these observations are based are summarized in Table 3.

Unmineralized Meguma Group greywackes and slates average 1 to 2 ppb gold (Thorpe and Thomas, 1976; Brooks *et al.*, 1982; Crocket *et al.*, 1983). Harrigan Cove greywackes and slates, averaging 8.7 and 8.0 ppb gold, carry at least four times the gold content of Meguma Group rocks from unmineralized areas. Although data are limited, an average arsenic content of 2.3 ppm (Crocket *et al.*, 1983) is suggested for unmineralized greywacke, so the Harrigan Cove greywackes then average 423 times higher arsenic than unmineralized greywacke using the averages in Table 3. Unmineralized

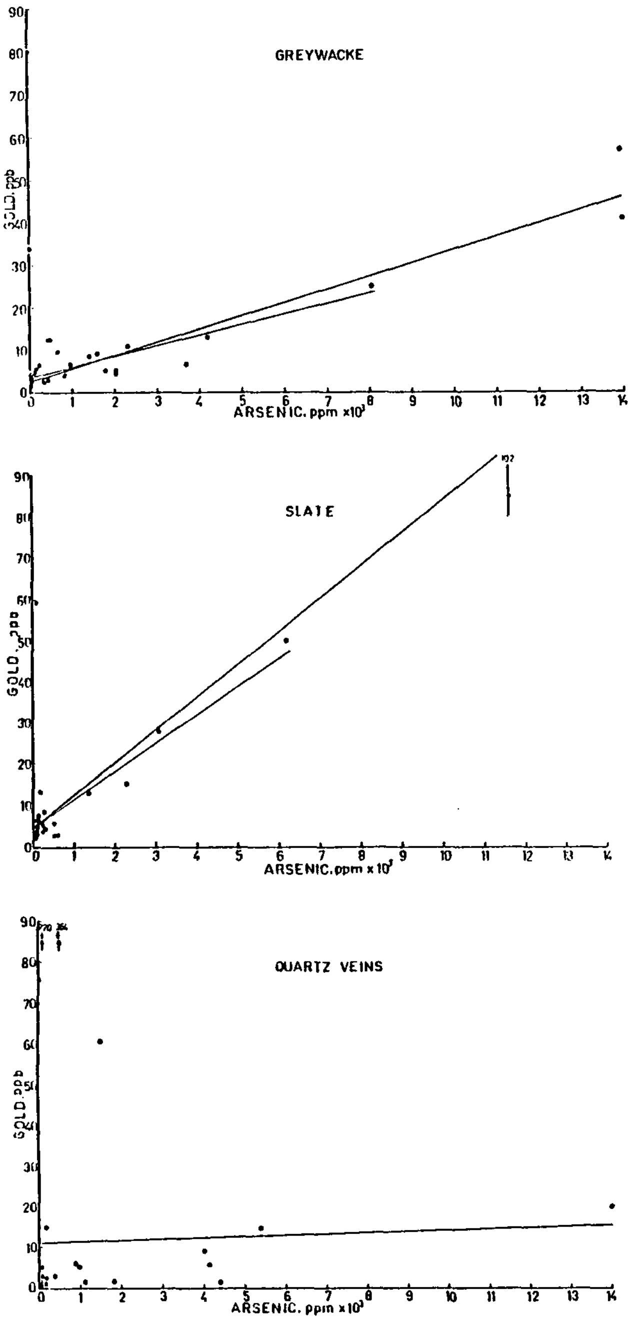

Figure 6. Gold-arsenic correlations at Harrigan Cove in (a) greywacke, (b) slate, and (c) quartz veins. Least squares fit lines are for the total (long) and $\bar{x} \pm 2$ populations (short).

Meguma Group slate from the Ecum Secum, area averages 2.5 ppm arsenic (Crocket et al., 1983), but the literature suggests a somewhat higher value, 13 ppm, may be typical of arsenic in shale (Onishi, 1969a). If an arsenic content of 10 ppm is taken as typical of slates from unmineralized areas, average Harrigan Cove slate (Table 3) is enriched in arsenic by a factor of 55.

The average antimony content of Harrigan Cove rocks does not indicate the presence of anomalous background levels of this metal. Onishi (1969b) suggested 1 to 2 ppm antimony is typical of shales and Harrigan Cove slates average 3.5 ppm antimony.

Thus, Harrigan Cove greywacke and slate, representing a mineralized district, are significantly higher in gold, and much higher in arsenic, than similar rock types from unmineralized areas. The common presence of arsenopyrite in Harrigan Cove rocks, particularly greywackes, is an obvious indication of the higher arsenic levels of the district.

The average gold content of the Harrigan Cove quartz veins is 62 ppb. Quartz veins provide the best indication of mineralization in that visible gold is occasionally seen in quartz vein outcrops, analyses return gold values of up to 10 ppm and samples are often highly anomalous in gold (i.e., 10 times the threshold level of 20 ppb). Unfortunately, no comparative body of data is available for quartz veins of an unmineralized area, and thus the gold levels characteristic of such veins cannot be estimated.

Relationship of Gold, Arsenic and Antimony to Lithology

Average metal contents (Tables 2a and 2b) indicate that greywacke and slate carry approximately the same gold contents. This equivalence is apparent whether locality averages (Table 2a) or total population averages (Table 2b) are compared. As greywacke is the most abundant lithology, it is a more important reservoir of gold than is slate. Quartz veins contain higher gold concentrations than the host rocks in three of the four localities, and on a basis of comparing averages for all data. However, gold is concentrated to variable degrees in quartz veins. In

Table 3.

COMPARISON OF AVERAGE AU AND AS CONTENTS OF ROCKS FROM HARRIGAN COVE WITH THOSE FOR UNMINERALIZED MEGUMA GROUP ROCKS AND LITERATURE VALUES FOR THESE LITHOLOGIES

Area of Sample	Lithology	Au, ppb	As, ppm	Ref.
Harrigan Cove	greywacke	8.7	972	6
	slate	8.0	549	6
Unmineralized Meguma Group Rocks				
Ruth Falls syncline	greywacke	1.2	2.3	3
Ecum Secum area	slate	1.7	2.5	3
Oldham area (core several hundred metres from nearest known minerallization)	greywacke	0.62	-	5
	slate	2.0	-	5
Sherbrooke area	whole rocks (slate, greywacke, granite)	1.0	-	1
Literature Survey	sandstones	3.0	1	2,4
	shale	2.5	13	2,4

1. Brooks et al., 1982.
2. Crocket, 1974.
3. Crocket et al., 1983.
4. Onishi, 1969a.
5. Thorpe and Thomas, 1976.
6. This study.

the Central North and Central South localities quartz veins contain about twice as much gold as do greywacke or slate, while South Trench veins contain about 10 times as much gold as the associated lithologies.

The average arsenic contents (Table 2a) of greywacke are 1.5 to 9 times greater than those of slate at three of the four localities sampled, including the North, Central North and Central South localities. The South Trench, an arsenic-poor locality shows the opposite trend. In the Central South locality, where the most extensive sampling was carried out, greywacke averages 9 times the arsenic content of slate. Average arsenic in greywacke is 4 to 25 times higher than in quartz veins, with the South Trench again an exception. In the South Trench higher arsenic is present in quartz veins than in greywacke. Thus, highest average gold contents characteristically occur in quartz veins, whereas the highest average arsenic levels occur in greywacke.

The distributions of antimony is similar to arsenic. The metal is lower in quartz veins than in slate or greywacke, and higher in greywacke than in slate. The differences in antimony content of greywacke and slate are less than for arsenic. For example, at the Central South locality greywackes contain 3 times more antimony than do slates, whereas their average arsenic content is nine times that of slate.

Differences in Metal Contents by Locality

One of four localities, the South Trench, is characterized by different proportions of metals than the other three. Very low arsenic (21 to 86 ppm) and relatively high gold (21 to 289 ppb) prevail in South Trench samples. The one exception is a slate (S1E1) with both high gold and high arsenic contents (Table 1e), which carries 1 to 2 cm euhedral arsenopyrite crystals. The South Trench greywackes are relatively high and variable in total carbon content but there is no simple sample-by-sample correlation of high carbon with high gold. Both greywacke and slate carry abundant sulphide, mainly pyrrhotite. The South Trench is the one locality where gold does not correlate with arsenic and where a partial sulphide control of gold contents seems likely.

Relation of Total Carbon to Lithology and Gold Content

For the entire Harrigan Cove suite average carbon contents of greywacke and slate are essentially identical, and about 3 times higher than in quartz veins. On a locality by locality basis slates and veins are relatively uniform in carbon content, buy greywacke is more variable. The average carbon content of south Trench greywackes is more than twice that of South Trench slates. This is the only locality where greywacke is much higher than slate in carbon. Calcite is a common accessory mineral in greywacke, and is presumably the main source of carbon in these rocks. Calcite is also seen in slates, particularly in quartz rich clots, but some disseminated graphite is also present. For comparison, slates from unmineralized localities in the Ecum Secum area average 0.11 wt. % CO_2 (Crocket et al., 1983) or about 3 times less than Harrigan Cove slates. Gold vs carbon correlation coefficients (Table 4) show no significant correlation of these elements on a sample-by-sample basis. However, on average, the carbon-rich South Trench greywackes are also high in gold.

Interelement Correlations

Correlation coefficients for gold, arsenic, antimony and CO_2 are summarized in Table 4, and plots of gold vs arsenic in greywackes, slates and quartz veins are shown in Figure 6a, b and c. Antimony and arsenic correlate strongly in all lithologies suggesting that antimony substitutes in the arsenopyrite structure,

Table 4.

INTERELEMENT CORRELATIONS FOR AU, AS, SB AND CO_2 IN HARRIGAN COVE GREYWACKE, SLATE AND QUARTZ VEINS

	Au	As	Sb	CO_2		Au	As	Sb	CO_2		Au	As	Sb	CO_2
Au		.84	.72	.06	Au		.84	.88	.32	Au		.06	.13	.10
As			.89	.16	As			.97	.09	As			.98	.32
Sb					Sb					Sb				
CO_2					CO_2					CO_2				

particularly as no discrete antimony minerals were observed. Gold correlates equally strongly with arsenic in greywacke and slate, but not in quartz veins. Carbon is not significantly correlated with any metal in any rock type.

These correlations suggest that gold distribution and concentration in slates and greywacke are controlled by arsenopyrite whereas in quartz veins other minerals, probably native gold and sulphides, are additional important hosts of gold. High gold in Meguma Group arsenopyrite was documented by Brooks et al. (1982). However, correlations must be treated with some caution due to the highly skewed character of the data whereby one or two very metal rich samples contribute strongly to the correlation. The plots in Figure 6 which include the data from all four sampling areas show least squares fits for both the total and $\bar{x} \pm 2\sigma$ populations. The background portion of the population is also indicated by the area enclosed by the threshold values for gold and arsenic (see following section). Within the population represented by background values interelement correlations are very low.

The South Trench is characterized by different proportions of gold and arsenic than other localities in that samples enriched in gold are often low in arsenic. If they are included in the greywacke population r is reduced to 0.5. The greywacke correlations might be interpreted to suggest that in Harrigan Cove greywacke as a whole, gold and arsenic are only moderately correlated. Alternatively, it might be suggested that in most greywacke gold and arsenic are strongly correlated in a positive sense, probably because greywacke is the preferential reservoir for arsenopyrite which in turn is a strong concentrator of gold. Where arsenopyrite is low, as in the south Trench, some other control on gold distribution, probably sulphide, becomes significant. The latter interpretation is preferred.

Threshold Metal Values

As previously noted, the average gold and arsenic contents of Harrigan Cove rocks indicate a modest enrichment in gold and a very strong enrichment in arsenic by comparison with similar Meguma Group rocks from unmineralized areas. The gold enrichments in greywacke and slate are of geochemical, but not economic, significance. It is useful to establish the threshold values in order to identify anomalous metal values within the background represented by the Harrigan Cove rocks. The metal populations are not defined by any simple distribution. The histograms in Figure 5 suggest that much of the gold data lie in the 0 to 10 ppb range for slate and greywacke. The greywacke data show a nearly normal distribution for gold at values up to 7 ppb, with the remaining 34% of the population represented by only one sample in any one ppb interval. This break in distribution pattern at 7 ppb suggests a threshold between background and anomalous populations at about 7 ppb. For slate most of the gold data are in the range 0 to 9 ppb, with the remaining 24% represented mainly by single values in any one ppb interval. If the greywacke and slate data are plotted on cumulative probability graphs, slope discontinuities occur at 7 ppb in the greywacke plot and 10 ppb in the slate plots. A threshold value of 10 ppb gold is suggested as differentiating background and anomalous gold in both lithologies. Several clusters of data in the 0 to 20 ppb range characterize the distribution of gold in quartz veins. The most pronounced discontinuity in a cumulative probability curve is at 20 ppb and this value is taken as the threshold value for gold in quartz veins. Similar considerations suggest thresholds of 2000, 300 and 300 ppm arsenic in greywacke, slate and quartz veins, respectively. These threshold values are plotted on the correlation diagram in Figure 6.

Lithological and Spatial Associations of Anomolous Gold

Based on the threshold values just noted, 27% of the 85 analysed samples are classified as anomalous. The distribution of anomalous samples by lithology is summarized as follows:

Lithology	No. of Samples	Samples with Anomalous Gold Number	Average Au, ppb	%
Greywacke	32	9	32	28
Slate	29	7	40	24
Quartz veins	24	7	1650	29

Thus, approximately the same percentage of samples from each of the three different lithologies carry anomalous gold. There are, however, significant differences in the gold content of the anomalous suites in that anomalous quartz vein samples generally exceed the threshold level far more than anomalous greywackes or slates. Another difference in the quartz vein and greywacke-slate anomalous suites is that about 70% of the anomalous greywacke-slate samples are also anomalous in arsenic whereas only 40% of the quartz vein suite is also anomalous in arsenic. This observation suggests that anomalous gold in the veins occurs as the native metal or in association with an arsenic-free phase more frequently than in the host rocks where a very close association with arsenopyrite must prevail.

DISCUSSION AND GENETIC CONSIDERATIONS

Genetic models for Meguma-hosted gold deposits are critically dependent on an understanding of the formation of the host quartz veins. They should also explain certain generalizations on the controls of mineralization many of which were noted in the early work of E.R. Faribault (1899): 1) high grade veins workable for gold are parallel to bedding planes, 2) such veins are hosted mainly in Goldenville Formation slates, 3) these veins usually occur at well defined points along anticlinal fold crests, particularly the centres of elliptical domes, and 4) such bedding-parallel veins are higher grade near the intersections with branching veins or angulars, and in minor folds or rolls. Those aspects of quartz vein formation on which consensus is lacking are the timing of vein emplacement, the mechanism of vein emplacement and the origin of the vein fluids.

The various hypotheses offered are wide ranging. In some it is proposed that the stratiform veins are essentially synsedimentary. Hunt (1868) and Hind (1869) proposed syngenetic models while recent contributions include those of Haynes (1983), who argued that the earliest stratiform veins formed as siliceous sinters in submarine, hydrothermal-vent hot-spring systems, and Kretschmar (1983) who suggested that the stratiform veins are chemical precipitates from hydrothermal silica-rich brines generated by convectively circulating seawater on the flanks of young spreading centres. In other hypotheses the veins are regarded as epigenetic and to have developed in response to deformation and/or regional metamorphism, but the timing of vein emplacement with respect to folding and metamorphism are matters on which opinions differ. Faribault (1899) directly linked vein formation and folding, and advocated that folding and vein formation occurred slowly and intermittently from solutions of local derivation. Keppie (1976) also linked folding and vein formation directly. On the other hand, Graves and Zentilli (1982) think that vein formation preceded folding, which in turn antedated cleavage development. They further argued that vein fluid introduction took place by hydraulic fracture during greenschist metamorphism and that vein mineral precipitation was rapid. Henderson (1983a) recognized three principal types of veins which were termed bedding-parallel, en échelon and AC veins. Through analysis of bedding-cleavage-vein relationship he concluded that the bedding-parallel and en échelon veins formed early in the strain history of folding at the time of cleavage formation, which was coeval with greenschist metamorphism. AC vein formation was late in the folding history. From vein fabrics and theoretical considerations it was argued that veins were formed by fluids of local derivation that were introduced by hydraulic fracture. Henderson (1983b) also showed, using particularly well developed examples from Harrigan Cove, that the crystal fabric in some vein quartz is indicative of vein formation by repeated hydraulic extension fracturing, a mechanism that implies veins are open to fluid intermittently over a protracted period of time.

A detailed assessment of these various hypotheses is beyond the scope of this discussion. However, those models which regard quartz vein formation as an integral component of the deformational history are preferred because an expected consequence is a preferential localization of veins in specific structural environments, as for example, anti-clinal fold crests. Henderson's analysis of the timing of vein emplacement largely evolves from measurable properties of the rocks and is preferred.

The origin of the vein fluids is also highly problematic. A brief survey noting the main suggestions may be found in Keppie et al., (1983). Having advocated an emplacement of vein fluids by hydraulic fracturing early in the history of folding and in keeping with the concept that both folding and cleavage development are a response to deformation of Meguma rocks (Henderson, 1983b), it is suggested that vein fluids are also, in part at least, an integral product of the deformation (Clifford et al., 1983). The specific process is thought to be pressure solution which generated the spaced cleavage prominent in the greywackes and which is accompanied by the loss of at least 10% of the original quartz content (Fueten et al., this volume). A source of aqueous fluid is required to dissolve the quartz, but a significant proportion of the quartz in the veins is probably of local derivation.

The most significant generalizations bearing on the gold mineralization process arising from our geochemical studies are the following: 1) Harrigan Cove greywackes and slates are slightly enriched in gold and very strongly enriched in arsenic relative to similar lithologies in unmineralized Meguma terrane, 2) the highest arsenic concentrations are usually found in greywacke and the lowest in quartz veins, 3) the highest gold concentrations are usually found in quartz veins, whereas greywacke and slate contain lower and approximately equivalent gold contents, 4) strong positive correlations between gold and arsenic are typical of slates and greywackes, whereas very weak correlations are typical of quartz veins, 5) enrichment of gold can occur without a corresponding enrichment of arsenic as is found at the South Trench locality.

The first generalization is thought to reflect a fundamental aspect of the mineralization process: an early introduction of arsenic and gold leading to a large increase in arsenic and a slight increase in gold in both greywacke and slate on a district-wide scale. The formation of bedding-parallel quartz veins is also an essential element of the mineralization process. However, bedding-parallel quartz veins are common in the Meguma terrane and many are barren of gold, showing that vein formation does not necessarily lead to mineralization. It is suggested that introduction of metals on a local scale is an early and essential stage in the mineralization process of Meguma rocks. If deformation then produces favourable structures in a local area with elevated metal content, mineralized veins may result.

Initial metal enrichment at Harrigan Cove probably involved introduction of arsenic followed by gold. The timing of these events is difficult to constrain. It is thought that a syngenetic origin is unlikely because a preferential concentration of arsenic in slate rather than greywacke would be expected. The limited discussions on the marine geochemistry of arsenic (Onishi, 1969a; Bostrom and Valdes, 1969) indicate that arsenic may be fixed in the marine environment by adsorption on ferromanganese or on fine clay-sized platy minerals or by organic concentration, all processes which would tend to result in accumulation of the metal in argillaceous members of the Meguma Group. The rapid deposition of greywacke A units from turbidity currents cannot have been favourable for any type of chem-absorption process to concentrated arsenic from the marine depositional environment. However, it is in the greywackes that the highest arsenic concentrations prevail. The explanation offered is that fluid circulation in Meguma rocks occurred mainly in greywacke, rather than in slates, because of much higher early post-lithification permeability and porosity. Thus, a preferential loading of greywacke with metals is expected if metals were introduced in fluids at some post-lithification stage after diagenesis and dewatering. Alternatively, the slates should have been the main arsenic reservoirs if arsenic was fixed in the marine environment during sedimentation. The precise timing of this proposed arsenic introduction is uncertain but, as the deformation and metamorphism would tend to reduce primary rock porosity and permeability, it is suggested that arsenic enrichment occurred prior to, or in the very early stages, of deformation.

Migration of arsenic and gold away from veins must also be considered as a mechanism for generating metal enrichment in host rocks. The common occurrence of arsenopyrite along vein-wallrock contacts suggests that some migration of arsenic occurred, at least within the veins. However, several aspects of arsenic (and gold) distribution in the Harrigan Cove case argue against the concept that all metal introduction into host rocks is due to quartz vein formation. The proportions of arsenic and gold in the veins and greywacke host rocks are such that the arsenic-to-gold ratio in greywacke averages approximately four times that of the quartz veins. Considering the average lithic proportions of greywacke to quartz veins, about 7 to 1, the greywacke units represent an arsenic reservoir of major proportions compared to the quartz veins. If vein-forming fluids alone were responsible for arsenic in the host rocks, an extremely high initial arsenic concentration in the fluids would be required, as well as a highly efficient and selective mechanism of arsenic loss from the veins. Well defined arsenic concentration gradients from veins would be expected. None of these features are observed nor are they expected properties of the vein fluids. Also, if the veins were the sole source of metals in host rocks the high concentrations of arsenic in greywacke present difficulties. As it seems likely that vein formation was early in the strain history, and perhaps continued during folding, then vein formation must have occurred after a significant loss of primary porosity had occurred. Indeed, if hydraulic fracture is the vein fluid emplacement mechanism, porosity cannot have been high. Thus, the preferential concentration of arsenic in greywacke rather than in slate is less easily explained by emanation from veins than by an early introduction of arsenic antedating vein emplacement. The source of an arsenic-bearing fluid is of course problematical and is not directly addressed by the geochemical distribution data.

A modest gold enrichment, amounting to a four-fold increase relative to unmineralized Meguma rocks, is also characterized of the Harrigan Cove host rocks. While there is a strong positive correlation of gold with arsenic on a total sample population basis (Table 4), inspection of the averages for individual localities (Table 2a) indicates that the very strong concentration of arsenic in greywacke relative to slate does not apply to gold. Thus, at the well sampled Central South locality average As in A units is about nine times that in E units, whereas gold is only enriched by about 1.25 times in greywacke relative to slate in these rocks. It is suggested that sufficient arsenic (and sulfur) were introduced into the host rock to crystallize discrete minerals (arsenopyrite and pyrite or pyrrhotite) which serve to concentrate gold. Although most of the arsenic crystallizes in the greywackes, sufficient arsenopyrite forms in argillaceous rocks to effectively scavenge gold in this medium as well, particularly as very small amounts of gold relative to arsenic are involved. The precise mechanism by which gold was concentrated by sulpharsenides and sulphides is unknown, but an attractive possibility is electrodeposition as advocated by Bancroft and Gilles (1982). This mechanism would allow the gold contents of sulphides (and sulpharsenides) to substantially exceed theoretical equilibrium solubility in sulphide systems (Barton, 1969). Thus, fluids which effected district-wide metal enrichments need not have had a high gold content. The critical factors leading to gold enrichment were probably related more to the volumes of fluid available, the permeability and porosity of the host rocks, and, most critically to early saturation of these fluids with respect to sulphides and sulpharsenides.

The final stage in this polygenetic mineralization process was the generation of the vein fluids in response to pressure solution, or, ultimately, to deformation. In this process, although much higher concentrations of arsenic were taken into solution than gold, the proportions of gold to arsenic in the fluids exceeded that in the host greywacke by perhaps a factor of four, leading to the relative gold enrichment in the veins. An evaluation of the pressure solution process in a gold district presents the problem of looking at a rock-vein system after metal transfer has occurred. It is suggested that an early phase of the process can be seen in unmineralized areas where spaced pressure solution cleavage has developed. The cleavage zones in unmineralized greywackes of the Ruth Falls syncline with prominent spaced cleavage that was produced by pressure solution contain 3.6 times the gold content (Crocket et al., 1983). This suggests a significantly stronger concentration of gold than of arsenic in the cleavage domains. With the development of cleavage some channelling of fluid flow along cleavage is expected. Such fluid would then leach metals in somewhat different proportions than represented by their contents in the lithon. It is suggested that fractionation of metals in the pressure solution process is one means by which higher gold-arsenic proportions are developed in vein fluids.

As assumption implicit in this hypothesis is that the gold/arsenic ratios observed in the quartz veins are the same as those of the mineralizing fluids. While the extent of gold-arsenic fractionation in the vein-forming process cannot be directly evaluated, a hydraulic fracture-fill origin of bedding-parallel veins is a mechanism which probably involved rapid fracture propagation and rapid fluid emplacement (Graves and Zentilli, 1982; Phillips, 1972). Further, rapid crystallization from vein-filling fluids may occur (Phillips, 1972). Such characteristics would tend to minimize the potential for metal fractionation in the vein-forming process.

CONCLUSIONS

A polygenetic mineralization process is envisaged which integrates metal distributions in host rocks and veins with structural history. Vein fluid generation, spaced cleavage produced by pressure solution and folding are thought to represent response to deformation of the Meguma rocks. These processes may generate auriferous quartz veins, but it seems that some enrichment of the host greywacke and slates in gold at, or prior to, the onset of folding is an essential element in vein genesis. At Harrigan Cove arsenopyrite plays a key role as a gold-concentrator mineral resulting in a sub-ore grade initial enrichment of gold in host rocks. Deformation further upgraded the gold concentration by selective transfer of gold to fluids that formed the quartz veins.

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