

Geological and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological constraints on the timing of quartz vein formation in Meguma Group lode-gold deposits, Nova Scotia

Daniel J. Kontak, Paul K. Smith

Nova Scotia Department of Mines and Energy, P.O. Box 1087, Halifax, Nova Scotia B3J 2X1, Canada

Peter Reynolds and Keith Taylor

Department of Geology, Dalhousie University, Halifax, Nova Scotia B3H 3J5, Canada

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The results of geological and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological investigations of several gold districts hosted by the Meguma Group are presented. Observations at both the macro- (deposit to ore zone) and micro- (hand sample to thin section) scale indicate that quartz vein formation followed major Acadian folding and metamorphism (ca. 400 ± 10 Ma) and was broadly coincident with mafic-felsic magmatism at ca. 370 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of vein-fill mica and amphibole from the Beaver Dam, Moose River, Fifteen Mile Stream, Upper Seal Harbour and Caribou deposits indicate ages of ca. 380 Ma to ca. 362 Ma. The age data are interpreted to reflect discrete hydrothermal events with rapid cooling following crystallization of vein constituents. The age data do not reflect either variable amounts of resetting by later granitic intrusions or diachronous cooling. Genetic models that interpret the generation of the auriferous quartz veins as either before or during major Acadian folding are considered to be inconsistent with the present results. Instead, a model is favored that interprets quartz vein formation in the context of continued transpression of the Meguma Terrane following regional folding and metamorphism.

On présente les résultats d'études géologiques et géochronologiques [$^{40}\text{Ar}/^{39}\text{Ar}$] effectuées dans plusieurs districts aurifères au sein du Groupe de Meguma. Des observations tant macroscopiques (du gîte à la zone de minerai) que microscopiques (de l'échantillon à la lame mince) indiquent que la formation des veines de quartz suivit un métamorphisme et un plissement majeurs acadiens (env. 400 ± 10 Ma) et coïncida d'une façon générale avec un magmatisme mafique à felsique vers 370 Ma. Des analyses $^{40}\text{Ar}/^{39}\text{Ar}$ effectuées sur des micas et des amphiboles de remplissages de veine provenant des gîtes de Beaver Dam, Moose River, Fifteen Mile Stream, Upper Seal Harbour et Caribou révèlent des âges aux environs de 380 à 362 Ma. On interprète ces données d'âge comme le reflet d'épisodes hydrothermaux distincts avec un refroidissement rapide suite à la cristallisation des constituants filoniens. Ces données ne reflètent ni un degré variable de remise à zéro par des intrusions granitiques ultérieures, ni un refroidissement diachrone. On considère que les modèles génétiques interprétant la formation des veines de quartz aurifères comme précédant ou ayant eu lieu pendant le plissement majeur acadien, sont en contradiction avec les résultats actuels. En leur lieu, on favorise un modèle qui interprète la formation des veines de quartz dans le contexte d'une transpression continue de la Lanrière de Méguma à la suite d'un plissement et d'un métamorphisme régionaux.

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INTRODUCTION

The temporal relationship between mineralization and host rock is of fundamental importance in the genetic modelling of ore deposits, in a broad sense determining if the deposit is to be classified as syngenetic or epigenetic. In the case of Meguma Group lode gold deposits, the numerous theories suggested to explain the occurrence of auriferous quartz vein mineralization in lower Paleozoic metaturbidite rocks have focused on this relationship in only relative terms. That is to say, no absolute chronological constraints have been obtained for vein formation and, therefore, gold mineralization. Consequently, the inferred age of mineralization has been made with respect to regional folding and metamorphism (ca. 400 ± 10 Ma; see below) of the Meguma Group. Because this approach does not provide an absolute time for vein formation, a geochronological study of a

few selected deposit areas has been attempted in order to obtain the first absolute chronological data for the vein forming event.

The presence of hydrothermal mica (biotite, muscovite) and amphibole within mineralized veins from many of the gold districts (Newhouse, 1936) make the $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological technique applicable (Dalrymple and Lanphere, 1969). This technique provides not only information pertaining to the timing of the vein-forming event, but also some indication of the thermal history because of the differential temperature dependence of Ar diffusion in different minerals (e.g., Hart, 1964; Berger, 1975; Harrison and McDougall, 1980a, b).

In this paper we first discuss evidence for the age of vein formation based on field and petrographic observations at a few districts. Subsequently, results of $^{40}\text{Ar}/^{39}\text{Ar}$ studies conducted on material from five gold districts are presented. We conclude by discussing the implications of the above data and why an age of

ca. 370 Ma is favored for the time of vein formation. Preliminary results of this study have been presented elsewhere (Kontak *et al.*, 1988d, 1989a, 1989b, 1990c), whereas a more detailed account of the data for the Beaver Dam deposit has already been discussed (Kontak *et al.*, in press-a).

REVIEW OF PREVIOUS THEORIES FOR MEGUMA LODE GOLD MINERALIZATION

Faribault (1899) was the first person to thoroughly examine the lode gold deposits and he proposed the saddle-reef model based on his studies of more than 60 districts. In Faribault's model, veins are considered to have formed as a result of intermittent mineral precipitation, principally quartz, in crest regions of folds during deformation of the host rocks. Keppie (1976) and Boyle (1979, 1986) essentially concurred with Faribault's model. While syngenetic models can be dated to the 19th century (Hunt, 1868; Hind, 1869 in Haynes, 1986), Haynes (1986, 1987) provided the first thorough discussion of syngenetic processes in the context of modern environments (e.g., geysers). McBride (1978) also implied a certain amount of syngenetic enrichment prior to vein formation. Based on a detailed study of quartz textures in the veins and the relationship of veins to wall rocks, Mawer (1985, 1986, 1987) concluded that the syngenetic model was not valid. Instead, Mawer interpreted the quartz veins to be of syntectonic origin, but late in the deformation history of the area and synchronous with granite intrusion at ca. 370 Ma.

A magmatic origin for the gold mineralization was first suggested by Rickard (1912), but more thoroughly discussed by Newhouse (1936) based on the apparent zonal distribution of vein mineralogy with respect to the granites. Douglas (1948) concurred with this idea, while Hy (1987) suggested a relationship to the granites from both a structural and fluid reservoir point of view. More recently, Williams and Hy (1990) have modified Hy's model to accommodate results of recent isotopic studies (Kontak *et al.*, 1988b; Kontak and Smith, 1989) which indicate a non-magmatic source for the fluids.

Graves and Zentilli (1982), Henderson (1983) and Henderson and Henderson (1986) proposed a hydraulic fracturing model for the auriferous, bedding-parallel quartz veins. Both vein formation and cleavage development are considered to predate folding (Henderson *et al.*, 1986), with vein constituents derived locally from the host strata. In a similar model, Sangster *et al.* (1989) suggested that the veins formed during prograde, greenschist facies metamorphism, with the fluids originating in adjacent Meguma Group lithologies. Polygenetic or multistage scenarios for vein formation, involving several stages of fluid generation and potentially different sources, have been suggested by Fueten (1985), Crockett *et al.* (1986a, 1986b) and Kerswill (1988). Most recently, Kontak *et al.* (1988c, 1989a, 1990b, 1990c) have suggested that the gold deposits formed during a Late Devonian metallotectonic event at ca. 370 Ma which represented the convergence of metamorphic, magmatic and structural processes.

The above discussion indicates that diverse views exist with respect to the genesis of Meguma Group lode gold deposits. The

contribution of absolute chronological data could thus provide important constraints with which to reassess some of the genetic models.

REGIONAL GEOLOGICAL SETTING

The study area lies within the Meguma Terrane (Fig. 1), the most easterly terrane of the Appalachian Orogen (Williams and Hatcher, 1983). The Meguma Terrane was accreted to North America during the Early to Middle Devonian Acadian Orogeny (Keppie, 1982; Keppie and Dallmeyer, 1987), the boundary now represented by the east-west trending Cobequid-Chedabucto Fault System (Fig. 1).

The Meguma Terrane comprises three main lithotectonic units, namely Lower Paleozoic metasedimentary and metavolcanic rocks, large volumes of peraluminous and lesser metaluminous granitic rocks of Late Devonian age, and Late Paleozoic-Mesozoic sedimentary and volcanic rocks (Fig. 1). The Cambro-Ordovician Meguma Group, underlying most of the Meguma Terrane, consists of the lower, sandstone-dominated Goldenville Formation and overlying shale-dominated Halifax Formation. These Lower Paleozoic rocks were deformed (F_1) into upright, northeast-trending open folds with an associated axial planar cleavage (S_1) during the regional Acadian Orogeny. Lower greenschist to upper amphibolite facies metamorphism (Fig. 1) occurred slightly later than peak deformation, as isograds cut across structural elements (Keppie and Muecke, 1979; Muecke, 1984; O'Brien, 1985). An age of ca. 400 ± 10 Ma for metamorphism has been estimated from $^{40}\text{Ar}/^{39}\text{Ar}$ studies (Reynolds *et al.*, 1973; Reynolds and Muecke, 1978; Keppie and Dallmeyer, 1987; Muecke *et al.*, 1988).

Large volumes of granitoid rocks of ca. 370 Ma age (Clarke and Halliday, 1980; Reynolds *et al.*, 1981; Keppie and Dallmeyer, 1987; Krogh and Keppie, 1988) intruded the deformed Lower Paleozoic stratigraphy. In addition, $^{40}\text{Ar}/^{39}\text{Ar}$ data for mafic intrusions in the Liscomb Complex (Giles and Chatterjee, 1986) and dyke rocks along the eastern shore indicate synchronicity of mafic and felsic magmatism, whereas $^{40}\text{Ar}/^{39}\text{Ar}$ dating of high-grade metasedimentary and metavolcanic rocks of the Liscomb Complex suggest an age of emplacement for the metamorphic complex of ca. 375 Ma (Kontak *et al.*, 1989a, 1990a; Kempster *et al.*, 1989).

Continued transpression of the Meguma Terrane in the Late Devonian to mid-Carboniferous is manifested by the presence of northeast-trending shear zones in granites and metasedimentary rocks (Eisbacher, 1969; Mawer and Williams, 1986; Mawer and White, 1986; Kontak *et al.*, 1986; Horne *et al.*, 1988; MacDonald *et al.*, 1989; O'Reilly, 1988a) and resetting of $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr whole-rock and mineral ages (e.g., Keppie and Dallmeyer, 1987; Dallmeyer and Keppie, 1987; Reynolds *et al.*, 1987; Kontak and Cormier, in press).

GEOLOGY OF MEGUMA GROUP LODE GOLD DEPOSITS

Meguma Group lode gold deposits, hosted by Goldenville Formation lithologies, consist of a wide variety of vein-types

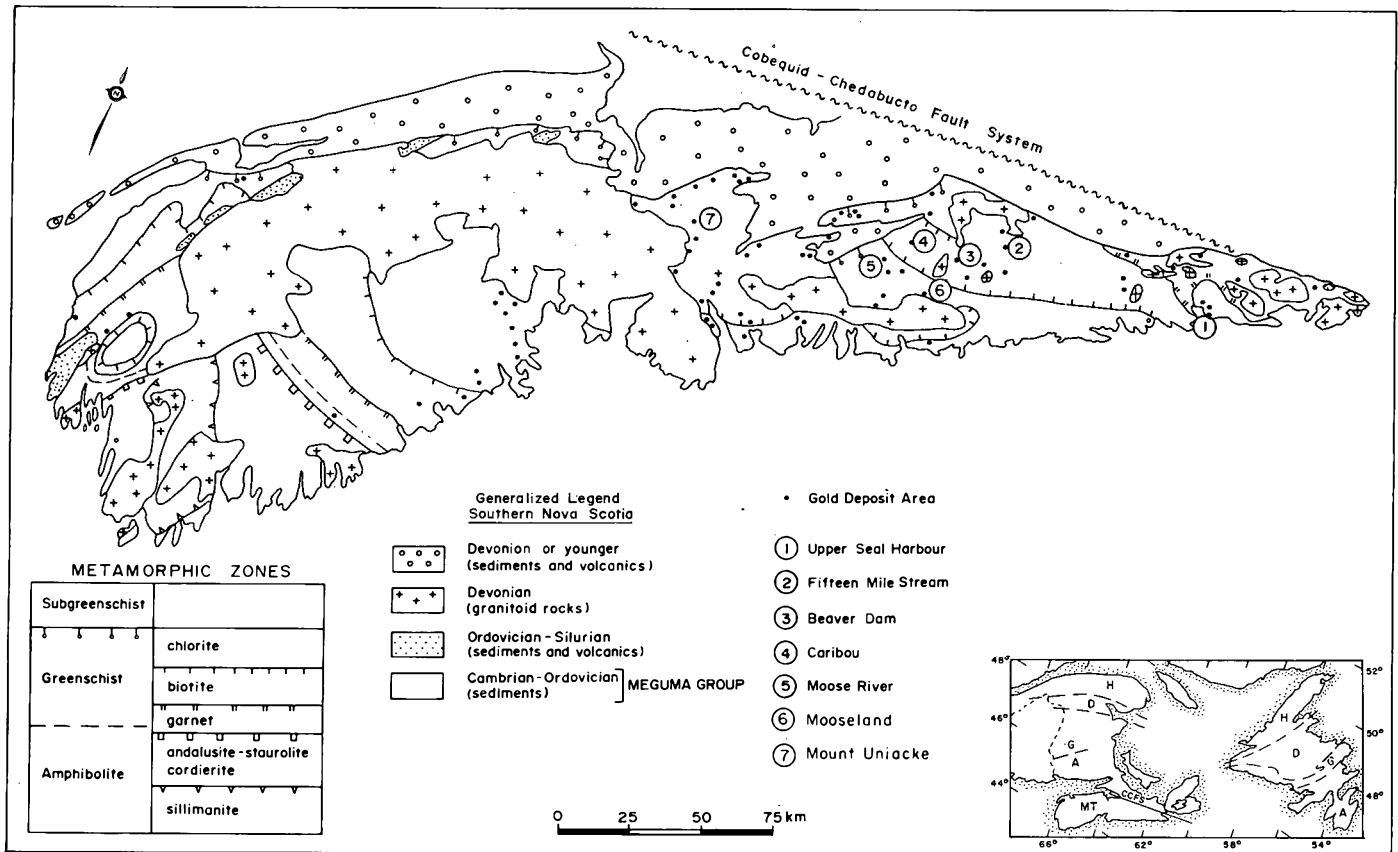


Fig. 1. Simplified geological map of southern Nova Scotia showing the distribution of historical gold producing districts and locations of deposit areas discussed in the text. Metamorphic isograds after Keppie and Muecke (1979). Inset map shows the location of the Meguma Terrane (MT) with respect to other terranes (A - Avalon, G - Gander, D - Dunnage, H - Humber) in the northern Appalachians (after Williams and Hatcher, 1983), CCFS - Cobequid-Chedabucto Fault System.

with the most important being the bedding-parallel type. Additional vein types include discordant veins (including large fissure or bull veins), stratabound veins at small angles to bedding, *ac* veins, and en echelon veins (see Henderson and Henderson (1986) for review of classification). The deposits generally occur in steeply dipping strata on the limbs of anticlinal or domal structures and veins are considered to have been emplaced within subvertical, brittle-ductile shear zones late in the folding history (Kontak *et al.*, 1990b; Williams and Hy, 1990). The widespread occurrence of vertical mineral lineations and boudinaged veins indicates a vertical sense of shearing, while the variably deformed nature of the veins and wall rocks indicate highly variable strain rates over short distances. Models presented by Kerrich and Allison (1978), Sibson *et al.* (1988), Hodgson (1988) and Roberts (1987), among others, to explain variably deformed auriferous quartz vein arrays adequately accommodate the features observed in the deposits.

Vein mineralogy (Fig. 2) varies considerably within and along strike of a single vein, and the abundance of silicate minerals, aside from quartz, increases with the metamorphic grade of the host rock. Thus, veins at the Forest Hill, Cochrane Hill and Beaver Dam deposits contain relatively more silicate minerals than do veins at the Tangier or Caribou deposits. A general paragenesis of the mineralogy is presented in Figure 2; two distinct stages of hypogene mineralization may be distin-

guished with a later, lower temperature stage 2 overprinting stage 1 where present. A variety of geothermometers, including Fe-Mg exchange between garnet-biotite, quartz-chlorite O isotope exchange, and fluid-inclusion thermometry, indicate that initial temperatures were ≥ 450 -500°C during stage 1 and subsequently cooled to ≤ 300 °C during stage 2. Sulfides were contemporaneous with both stages, but a larger proportion occur with stage 2. There is no textural evidence (e.g., prograde reactions, replacement textures, mineral zoning) indicative of a reheating event in any deposit; thus the veins record a single protracted mineralizing event.

AGE CONSTRAINTS FOR VEIN FORMATION INFERRED FROM FIELD RELATIONSHIPS

Relative timing relationships inferred from field relationships and petrographic observations provide some constraints with respect to the time of quartz vein formation. In the following section type examples are presented to illustrate this point.

Deposit scale observations

On the deposit scale, both the Caribou and Mount Uniacke gold districts are excellent illustrations of the importance of late structures as sites for quartz vein formation. In addition, the

	Stage 1	Stage 2
Quartz	—————	—————
Ca-rich plagioclase	—————	
Tourmaline	—————	--
Garnet	-----	
Amphibole	-----	
Biotite	—————	
Epidote	-----	
Apatite	-----	
Andalusite	-----	
Albite		—————
Muscovite	-----	—————
Carbonate		—————
K-feldspar		?
Sphene		-----
Rutile		-----
Ilmenite	-----	-----
Pyrite	—————	—————
Pyrrhotite	—————	—————
Chalcopyrite	—————	—————
Galena		—————
Sphalerite		—————
Arsenopyrite	—————	—————
Scheelite		—————
Hessite		—————
Greenockite		—————
Bi-Te sulphides		—————
Gold	??	—————

Fig. 2. Generalized paragenetic sequence for auriferous quartz veins in the Meguma Group. Note that the mineralogy as shown may not be present at any one deposit and that the two generalized stages are transitional in nature rather than representing an abrupt break (see text for more detailed discussion).

recent delineation of gold mineralization at the Touquoy Zone (Moose River district) demonstrates the role played by structure in determining the locus of mineralization, albeit barren of veining in this case.

Caribou gold deposit

The Caribou deposit is located well away from any known intrusion and stratigraphically lies just below the Goldenville-Halifax transition zone (Fig. 1). The strata consist of mixed psammite and pelite and the metamorphic grade is biotite zone of the greenschist facies, although in thin section the biotite porphyroblasts are seen to overgrow the main foliation. The strata are folded and define a northeast-trending anticline (F_1 structure) referred to as the Caribou Dome.

Two types of ore zones are present at the Caribou deposit (Fig. 3), these being interstratified or bedding-parallel veins (High Grade Vein system) and crosscutting veins (Main Ore Body). The bedding-parallel veins occur within slate beds intercalated with greywacke and in some cases may be followed over the anticlinal dome. In contrast, the Main Ore Body, which consists in plan view of an en echelon array of angular veins (Fig. 3), crosscuts both the stratigraphy and main foliation. The deposit is described in more detail by Bell (1948).

Mount Uniacke gold district

The Mount Uniacke gold district (Figs. 1, 4) occurs on the Mount Uniacke anticline or dome (F_1 structure). Most of the veins are of the interstratified or bedding-parallel type and all of the productive horizons mined were within subvertical-dipping strata on the southern side of the dome; only a few barren veins were present in the more shallowly dipping (60°) strata of the northern limb (Malcolm, 1929). The bedding-parallel veins occupy two contrasting structural settings, namely (1) parallel to the east-trending axis of the fold, and (2) in a subordinate flexure or bulge that emanates outwards from the central part of the dome for 300 m to the south. In the second case (Fig. 4) the bedding-parallel veins have been crumpled and crosscut by discordant quartz veins. The amount of quartz, and also gold ore, diminish away from the apex of these secondary parasitic folds.

Touquoy Zone (Moose River) gold deposit

The Moose River gold and tungsten (scheelite) district (Fig. 1), located north of the Musquodoboit Batholith by some 10 km, occurs where the Fifteen Mile Stream and Beaver Dam anticlines converge. The deposit area, hosted by greenschist-facies (biotite zone) rocks, consists of the eastern, gold-producing Higgins and Lawler mines and the western scheelite area. The quartz veins are dominantly the bedding-parallel type and are confined to a package of slates that are bounded by vein-free greywackes both to the north and south (Malcolm, 1929).

The Touquoy Zone of the Moose River district is located in the vicinity of the old Higgins and Lawler workings, in the northeastern part of the district. At this locality (Fig. 5) a fault-bounded section of black, graphitic argillite contains disseminated gold mineralization where it is highly carbonatized and sulphidized (pyrrhotite); mineralization disappears across the bounding faults. Gold-bearing pyrrhotite overgrows greenschist-grade mineralogy and is elongate parallel to the S fabric of the host rock, whereas the carbonate occurs as coarse, euhedral, inclusion-rich grains which show variable amounts of rotation (i.e., synkinematic growth in part).

Conclusions

The main conclusions from the cursory examination of these gold districts is that quartz vein formation and alteration (Touquoy Zone) at least in part post-dated the major Acadian folding event. At the Caribou and Mount Uniacke districts, the crosscutting zones occupy late structures indicating that some of the fluids responsible for vein formation must have been introduced late in the structural evolution of the Meguma Terrane. Unfortunately, the observations do not provide a minimum age constraint on the timing of vein formation, although Malcolm (1929) noted that the westward extension of the bedding-parallel veins in the Mount Uniacke district are apparently truncated by the 370 Ma South Mountain Batholith.

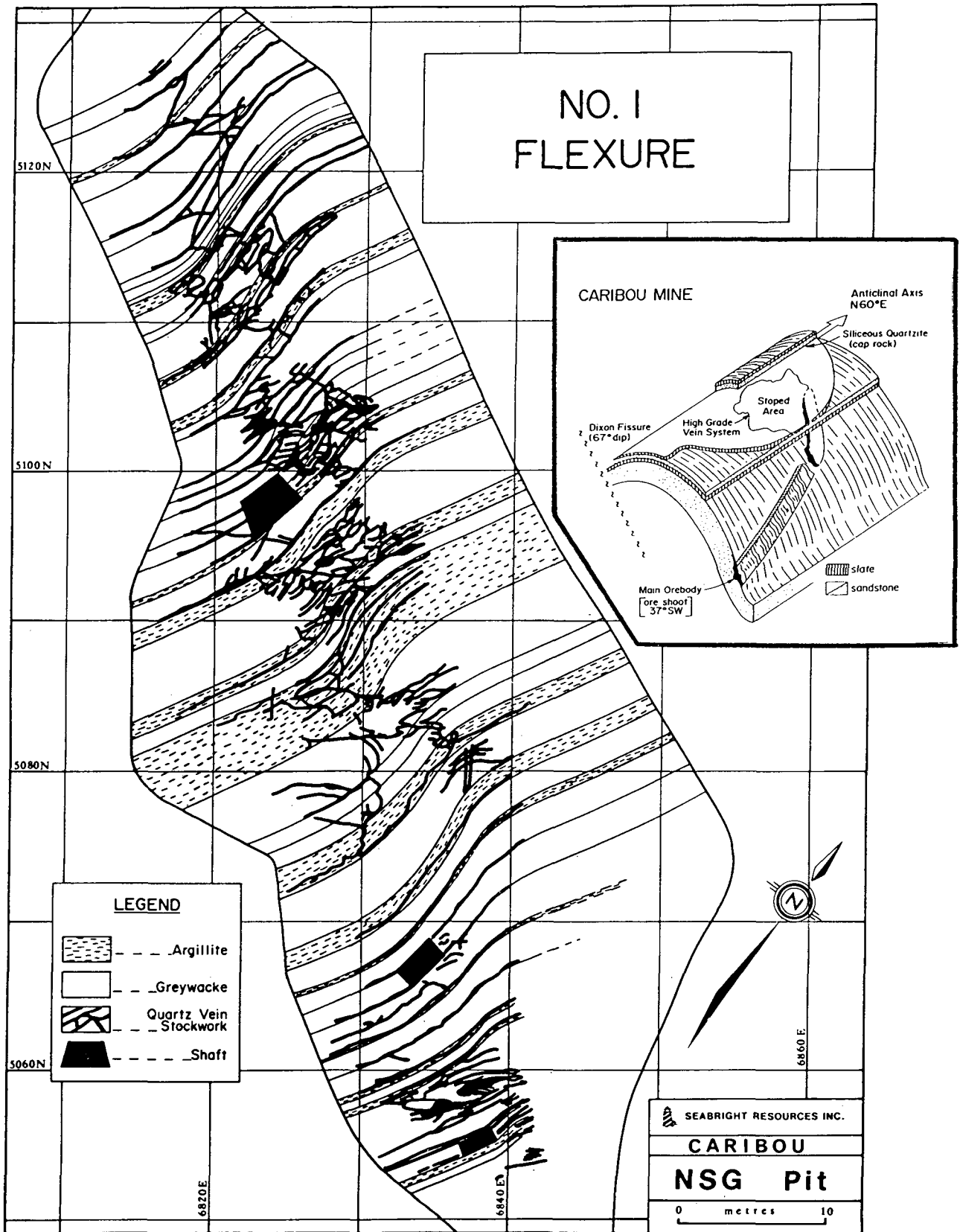


Fig. 3. Geology of the Caribou deposit. Inset map illustrates the generalized geology of the Caribou dome showing the location and extent of the two main ore zones mined (modified after a diagram prepared by S.J. Haynes, personal communication, 1984). Large figure shows plan map of the Main Orebody as exposed on surface (modified after map prepared by geologists of Seabright Resources). Note how the quartz veins in the plan map are clearly discordant and crosscut the stratigraphy, although a few are apparently bedding parallel on a local scale.

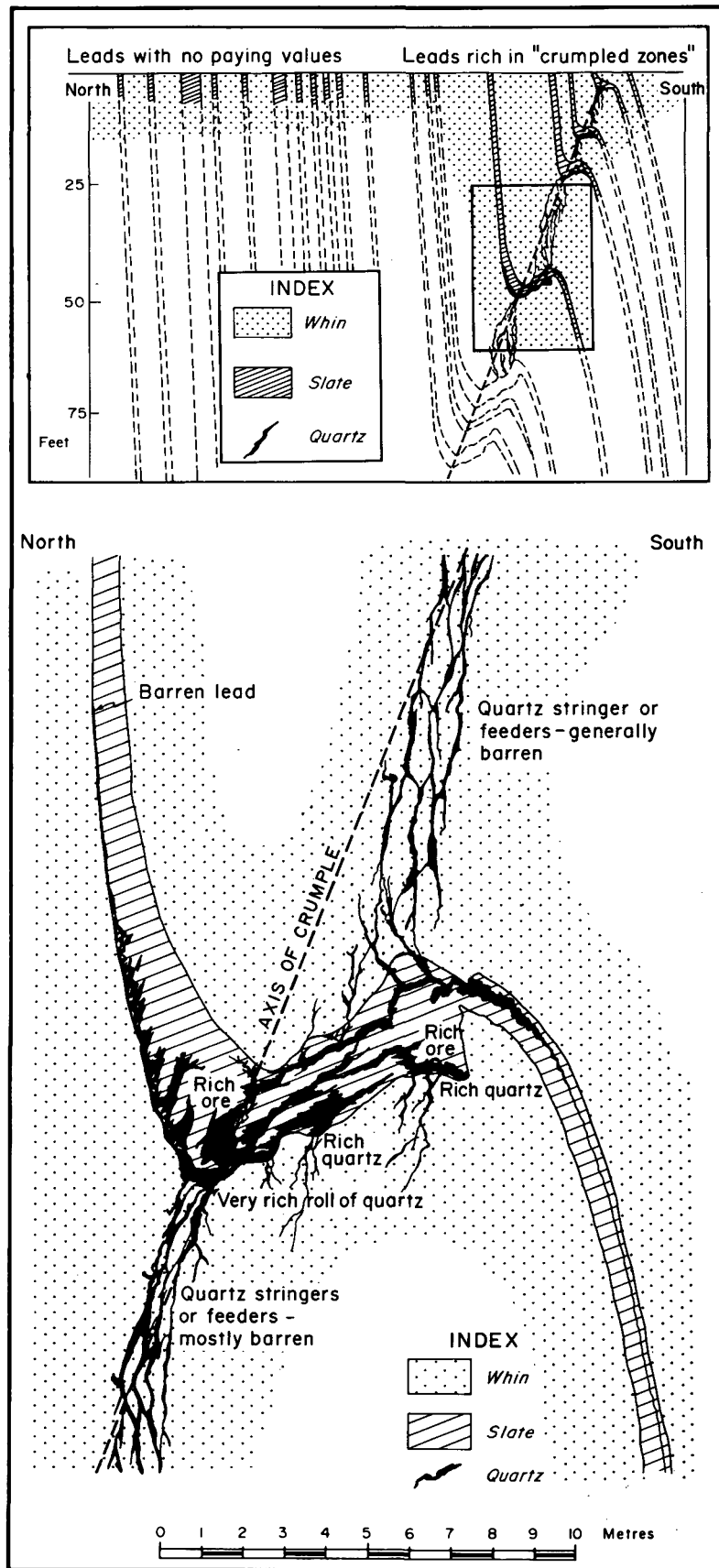


Fig. 4. Cross-section map of the Mount Uniacke deposit (after Malcolm, 1929). Details of the diagram are discussed in the text.

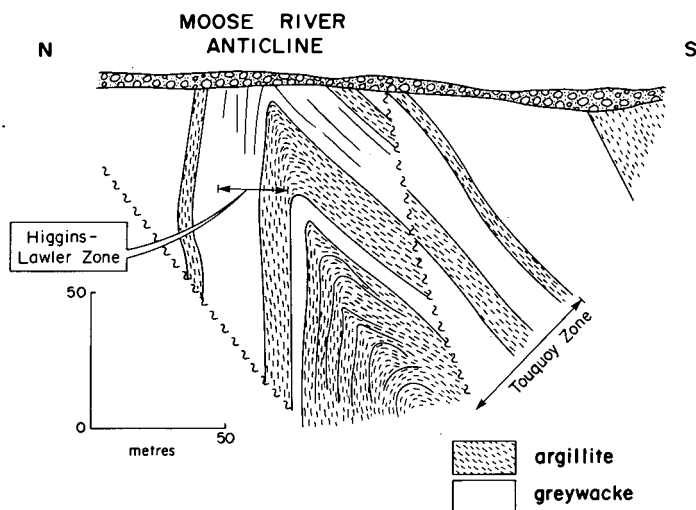


Fig. 5. Cross-section map of the Moose River anticline showing the stratigraphy of the area, location of the Higgins-Lawler Zone (quartz-vein hosted gold mineralization) and location of the Touquoy Zone mineralization (modified after map prepared by Seabright Resources).

Outcrop- and thin section-scale observations

Observations at the outcrop- and thin section-scale provide important relative timing relationships based on paragenetic relationships. In some locations such observations provide only equivocal information; however, in other areas unequivocal information regarding timing of vein formation is available. It is the latter localities that are discussed below.

Mooseland gold deposit

The Mooseland gold deposit (Fig. 1) is located immediately north of the 370 Ma (Reynolds *et al.*, 1981; Keppie and Dallmeyer, 1987) Musquodoboit Batholith on the axis of the Mooseland anticline (F_1 structure). The area examined in detail is located on both sides of the provincial highway running north from Tangier, some 7.5 km north of the contact between the aforementioned granite and Meguma Group metasedimentary rocks. The geology of the area relevant to this discussion is illustrated in Figure 6. Additional detailed studies of this area have been undertaken by Melvin (1987) and Williams and Hy (1990).

The study area occupies the axis of an anticlinal structure and consists of two lithological zones, a southern psammite-dominant zone and a northern pelite-rich zone. In the southern area are located the axis of the anticline and several large, massive coarse-grained quartz veins of bedding-parallel type that may be examples of saddle-reef veins. They are composite in nature and locally contain vugs infilled with euhedral quartz crystals of ca. 5 cm length. These veins are cut in part by variably deformed *ac* and discordant veins (Fig. 7).

In the northern part of the study area the most notable feature is the deformed nature of the host rocks and veins. The deformation (N-S compression) was so intense as to have created boudins

and pods from quartz veins, rotated veins into parallelism and caused extreme shortening of veins. There are, however, some veins (Fig. 7a, b) that do not record the effects of this deformational event. Another feature present in this area is the occurrence of elliptical-shaped, light-coloured minerals or mineral aggregates, henceforth termed "oikocrysts", homogeneously distributed throughout the pelitic units (Fig. 8a, b, c, d). In thin section the oikocrysts are seen to consist of quartz-biotite-chlorite-carbonate-ilmenite-rutile-sphene, with quartz-biotite the most prominent constituent (Fig. 8c). These oikocrysts, common to many deposits (e.g., Beaver Dam, Caribou, Fifteen Mile Stream), define a steeply dipping lineation in the plane of cleavage. The oikocrysts at Mooseland are interpreted to represent retrograded porphyroblasts related to contact metamorphism.

Figure 7 illustrates some important features observed in the northern part of the map area and summarizes the paragenetic sequence of events. In addition, examination of thin sections indicates that the dominant fabric in the rocks is a shear fabric (S_2) which overprints the regional slaty cleavage (S_1) (Fig. 8b, c, d, e, f). Hence, the timing relationships indicate that vein formation and attendant alteration (e.g., silicification) was post-hornfelsing of the pelites, presumably related to intrusion of the nearby Musquodoboit batholith at ca. 370 Ma, with subsequent deformation. Note that this is a generalized paragenesis and in fact a more protracted and complicated history of veining is probable (cf. Melvin, 1987).

Beaver Dam gold deposit

The Beaver Dam gold deposit, 1-2 km east of the northern contact of the River Lake intrusion (Fig. 1), occurs within a package of intercalated psammites and pelites on the southern, overturned limb of the Beaver Dam Anticline. Along the northern contact of the granite, Meguma Group metasedimentary rocks are cut by pegmatite and aplite, and contain an assemblage (biotite-muscovite-cordierite-garnet-andalusite-staurolite) which is synkinematic with respect to the rock fabric (Fig. 9a, b, c, d, f). Within the deposit area itself, metamorphism is of biotite grade and there are abundant elliptical-shaped mineral clots (i.e., oikocrysts) consisting of variable proportions of quartz-biotite-chlorite-sulphides-sphene-carbonate (Fig. 9g). These mineral clots show highly variable degrees of strain with aspect ratios varying from about 1:1 to 20-25:1.

Within rocks of the Beaver Dam deposit area petrofabric studies indicate the presence of a shear overprint fabric (e.g., Fig. 9h). In addition, Figure 10 illustrates that this late cleavage (S_2) is sometimes axial planar to folded quartz veins and crenulates an earlier cleavage (S_1). This overprinting cleavage is inferred to be the dominant cleavage in the Beaver Dam area.

Bedding-parallel veins are the most common vein-type, with lesser amounts of discordant and *ac* veins. The mineralogy of the veins is similar to that shown in Figure 2, with the exception of andalusite which is absent. In the western part of the deposit area, within the influence of the River Lake pluton, micro-veinlets of quartz \pm carbonate have crosscut andalusite porphyroblasts and retrograded the mineral to sericite (Fig. 9e, f).

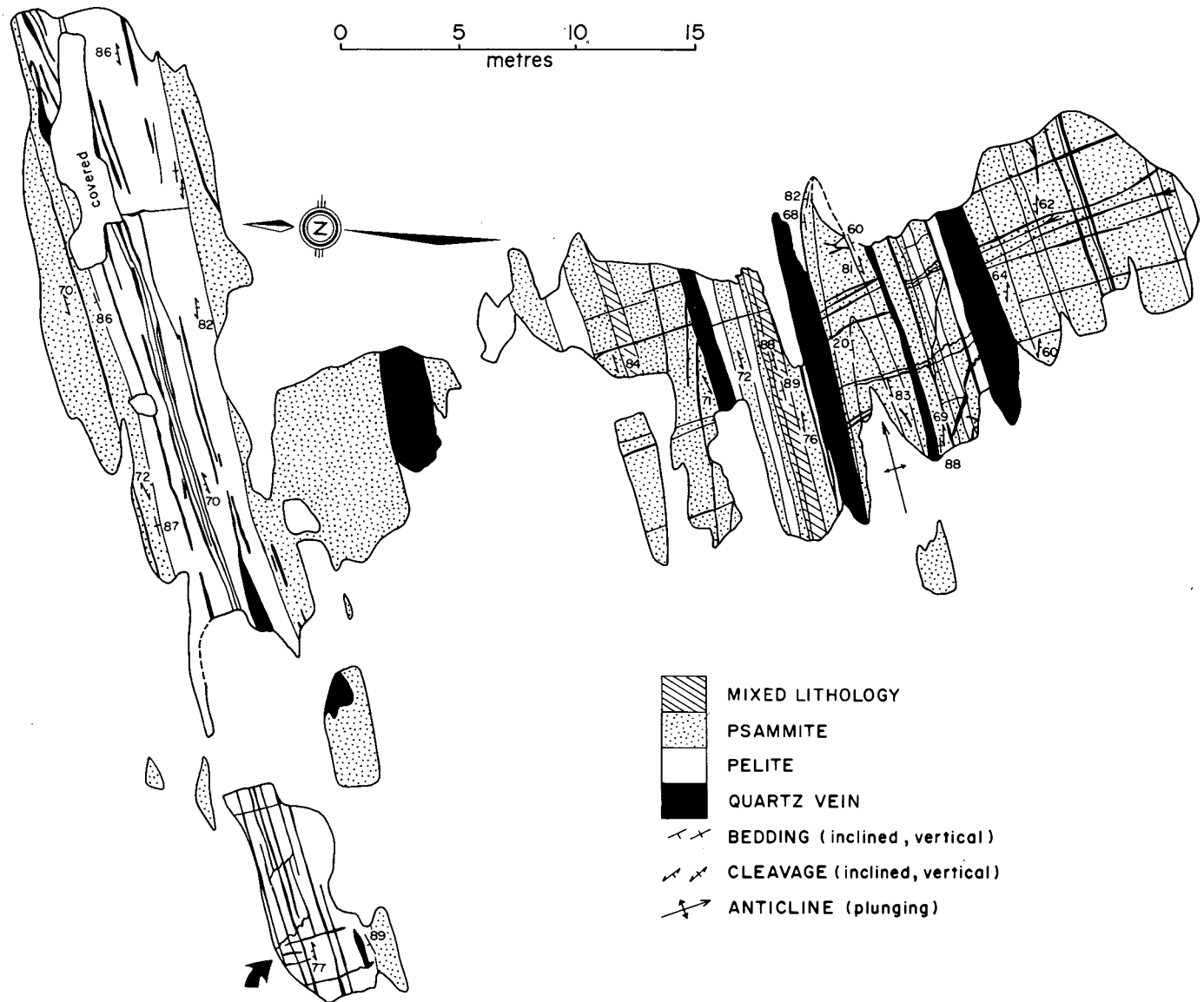


Fig. 6. Plan map of the Mooseland gold district (unpublished work of the authors) near the main anticline on the east side of the provincial highway. Location of outcrop area where drawings in Figure 7 are based is indicated by an arrow.

Fifteen Mile Stream gold deposit

The Fifteen Mile Stream gold deposit (Fig. 1) is located on a composite anticlinal structure which is part of a paired anticline (F_1 structure) that hosts the Moose River and Beaver Dam gold districts. The host rocks are typical metaturbidites, but with an unusually high ratio of pelite:psammite (Coates, 1987), and have been tightly folded into a series of three anticlines which plunge 20-30° east. The strata are steeply dipping to overturned (75-80°) on the southern limb, with 60-70° dips for strata on the northern limb. The host rocks are metamorphosed to biotite grade of the greenschist facies with large biotite porphyroblasts overgrowing the main cleavage (Fig. 11a). Although the dominant veins mined were bedding-parallel type, the highest grade intersections occur where these veins intersect cross-cutting angulars (Cameron, 1941). Coates (1987) noted that the most productive zones were spatially associated with a northeast-trending, steeply-dipping

shear zone. More detailed descriptions of the deposit area are found in Malcolm (1929), Cameron (1941) and Coates (1987).

Examination of the vein and wall rock lithologies in detail indicates the following: (1) biotite porphyroblasts overgrew the main foliation in the pelites (S_1 ?, Fig. 11a) and, more rarely, were truncated by veins (Fig. 11e); (2) hydrothermal biotite (?) is concentrated along fracture planes that crenulated the S_1 (?) fabric (Fig. 11b); (3) cleaved wall-rock fragments occur within veins (Fig. 11c); and (4) cleaved wall rock material extends into veins as narrow septa (Fig. 11d).

Conclusions

The main conclusions from the above observations at the Mooseland, Beaver Dam and Fifteen Mile Stream areas are as follows: (1) development of porphyroblasts and cleavage (S_1) predated some of the veining in these deposit areas; (2) porphy-

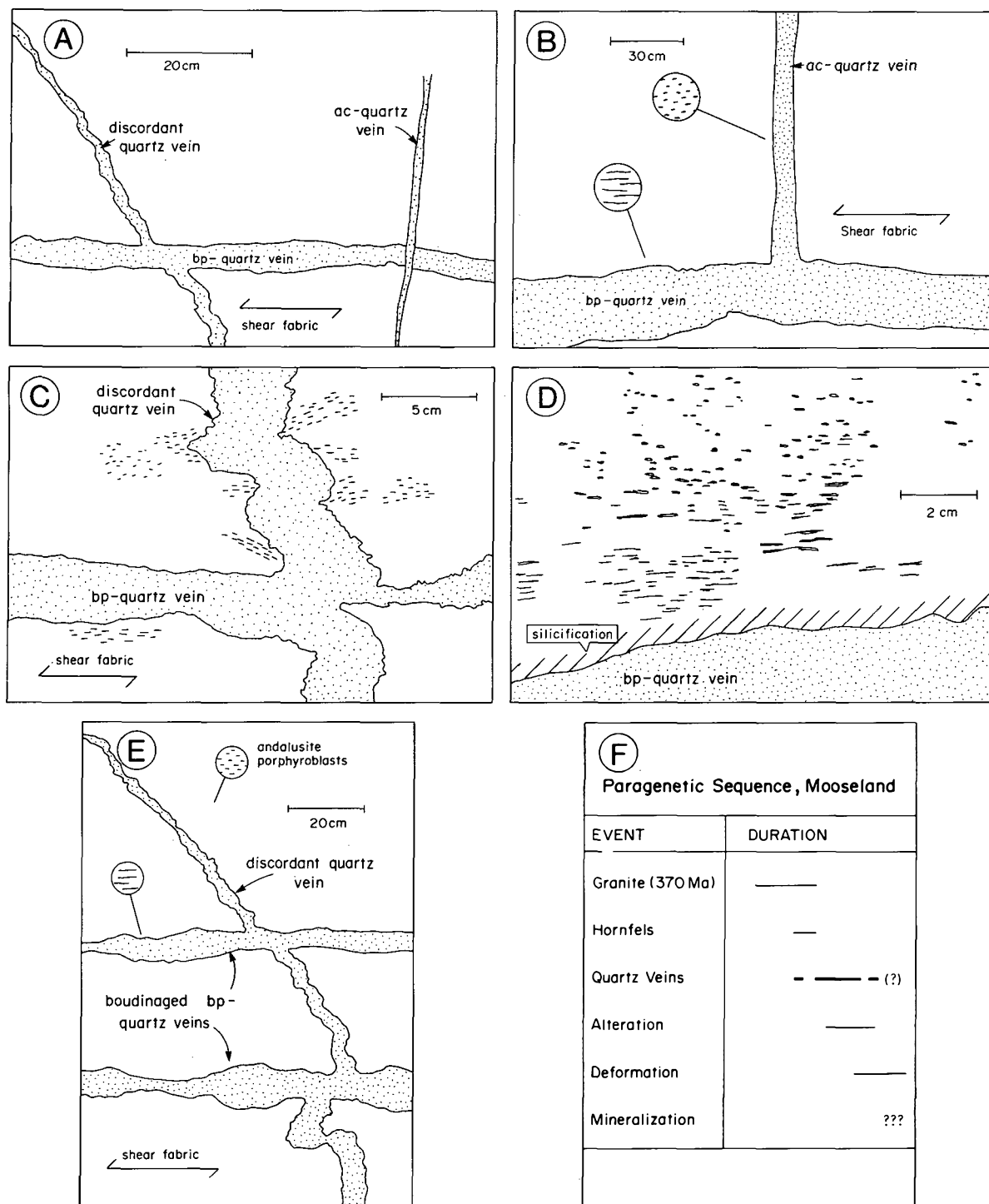


Fig. 7. Photograph tracings showing the relationship between different quartz veins, oikocrysts and deformation at Mooseland (see Figure 6 for location of the drawings). Note that the oikocrysts are flattened parallel to the shear cleavage in all the diagrams and that away from the bedding-parallel quartz veins the oikocrysts are not flattened. (a) Deformed bedding-parallel and discordant veins with later, apparently undeformed *ac* quartz vein. (b) Deformed bedding-parallel quartz vein with oikocrysts flattened (inset) parallel to the length of the vein. Late *ac* quartz vein with equant oikocrysts adjacent to it. (c) Deformed bedding-parallel and discordant quartz veins with flattened oikocrysts adjacent both veins. Note that the otherwise equant oikocrysts become flattened and stretched where they are proximal to the highly strained parts of the deformed, discordant quartz vein. (d) Close up of left side of area in (c) showing the flattened nature of the oikocrysts and the zone of alteration (silicification) where the oikocrysts are absent. Note the equant shape of the oikocrysts away from the bedding-parallel quartz vein. (e) Deformed, bedding-parallel quartz veins showing flattening of the oikocrysts adjacent the veins (compare insets). (f) Inferred paragenetic sequence of events for the Mooseland area based on the relationships observed in Figures a through e, photomicrographs in Figure 8 and information as discussed in the text.

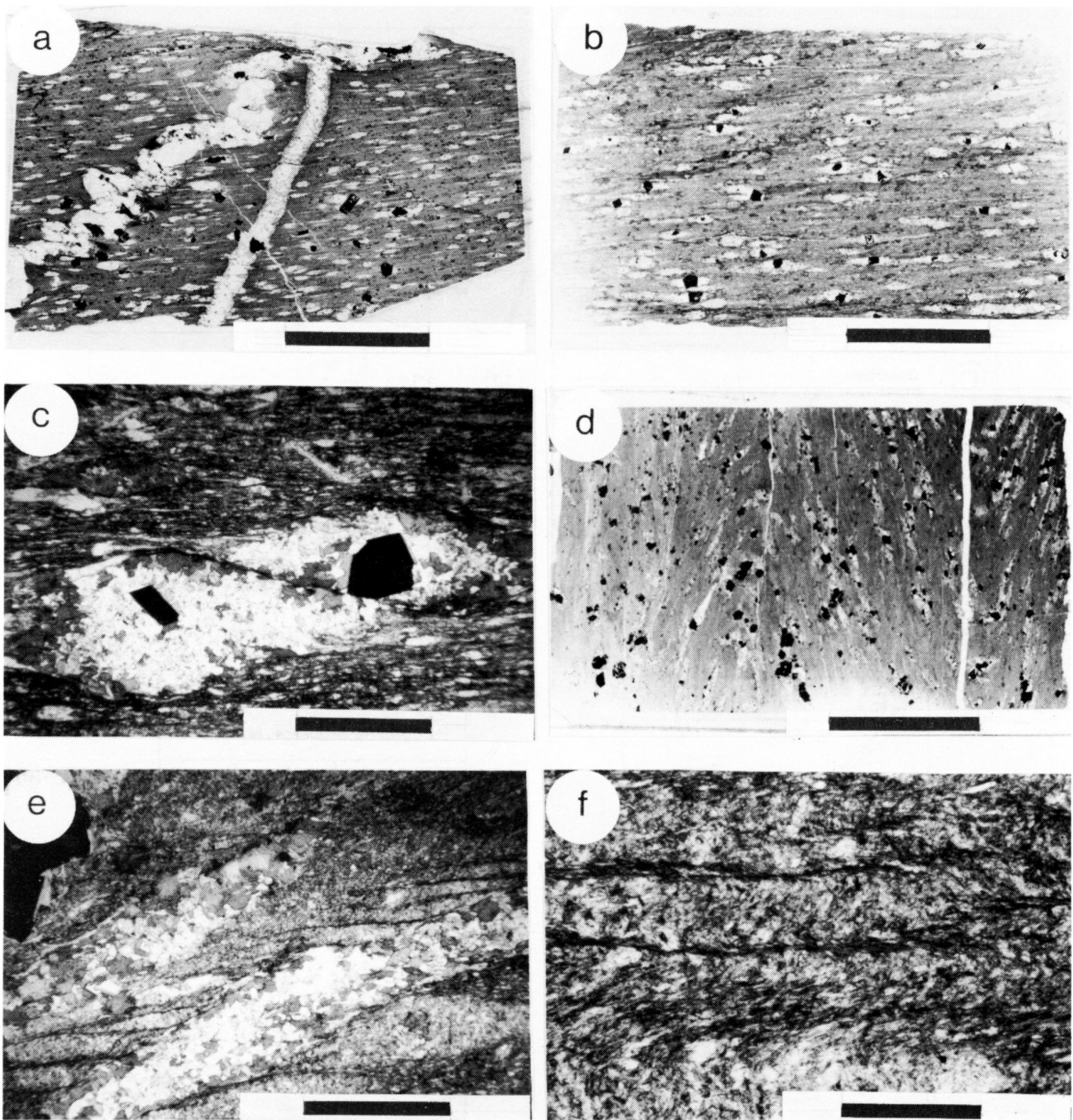


Fig. 8. Photomicrographs of wallrocks at the Mooseland gold district. All samples come from the intensely deformed, pelite-rich, northern part of the map area in Figure 6. (a) Wall rock pelite containing disseminated oikocrysts is cut by two generations of quartz veining. Note that the quartz vein on the left is strongly folded while the vein on the right is not folded and, in addition to quartz, contains abundant plagioclase along the vein margins. The flattening fabric is considered to represent an overprinting shear cleavage (S_2 , see below). Bar scale 1 cm. (b) Wall rock pelite containing homogeneously disseminated, quartz-dominant, flattened oikocrysts. Bar scale 1 cm. (c) Close-up of an oikocryst in the previous photo showing intergrowth of quartz, biotite (mainly along the margins), carbonate, sphene and sulphides. The euhedral opaque grains are arsenopyrite. Note that the shear fabric transects the oikocryst. Bar scale 0.5 mm. (d) Intensely deformed wallrock pelite containing abundant, elongate oikocrysts which define folds. The axes of the folds are colinear with the main fold in the Mooseland area (Fig. 6). The fabric present is considered to represent an overprinting shear cleavage which would be coplanar with the regional Acadian fabric in limb areas. Bar scale 1 cm. (e) Close-up of Figure 7d showing lozenge-shaped oikocryst on the limb of the fold. The well-developed, horizontal fabric is S_2 (shear cleavage) while the regional Acadian fabric (S_1) is crenulated and is subvertical in this photograph. Bar scale 0.5 mm. (f) Close-up of pelite in the hinge area of fold in Figure 7d showing the relationship between the shear cleavage (horizontal, S_2) and regional Acadian fabric (subvertical, S_1). Bar scale 0.5 mm.

roblast growth was in part synkinematic, and in part post-kinematic; (3) alteration of porphyroblasts was syn- to post-porphyroblast development; (4) if the porphyroblasts are related to intrusion of granites, then the age of veining is \leq ca. 370 Ma; and (5) the presence of an S_2 fabric indicates that the regional Acadian fabric (S_1) was overprinted by a later shear cleavage. The S_2 fabric deformed porphyroblasts at Beaver Dam and Mooseland; thus, the timing of D_2 is inferred to be \leq ca. 370 Ma.

⁴⁰AR/³⁹AR GEOCHRONOLOGICAL STUDIES

Sample localities and descriptions

Five areas were sampled for dating as part of our regional study of Meguma gold deposits in the eastern part of the Meguma Terrane (Smith and Kontak, 1986). In each area different amounts of surface and underground mapping, sampling and follow-up laboratory studies have been performed, as reported in Nova Scotia Department of Mines and Energy Report of Activities 1986-1989 (also Kontak *et al.*, 1990b and references therein). The following is a brief description of the material used for dating.

Beaver Dam gold deposit

Samples from the Beaver Dam area include a (1) biotite-muscovite monzogranite (RL-87-1) from the River Lake pluton, (2) a pegmatite/aplite segregation (NS-4S-86) cutting hornfelsed metapelites in the contact aureole of the River Lake pluton, and (3) vein material from the deposit itself. Vein sample CX-86-6 is from the western extent of the deposit area about 1 km or less from the River Lake pluton, and the remaining vein samples were collected during underground mapping in 1988. Both stages of hypogene mineralization (Fig. 2) are represented by the vein sampling. The composition of the amphibole analyzed is transitional between magnesio- to tschermakitic hornblende (representative analyses in Table 1) in the classification scheme of Leake (1978). More detailed descriptions of these samples are presented in Kontak *et al.* (in press-a).

Caribou gold deposit

Two samples containing hydrothermal muscovite were collected from the Caribou deposit during underground mapping in the fall of 1988. Sample CAR-88-50, from a discordant vein in the 558 crosscut on the 500-foot level near the Main Zone, consists mostly of quartz, carbonate and arsenopyrite, with muscovite coming from a muscovite-chlorite-carbonate clot along the vein-wallrock contact. The second sample, CAR-88-23, was collected from the 800-foot level, midway between the Main Zone and the A Zone on this level (the A Zone is a recently discovered zone of mineralization that occupies the same structure as the Main Zone and has similar features). The sample is from stockwork quartz mineralization and the vein assemblage at this locality consists of quartz-carbonate-chlorite-muscovite with ore-grade gold assays.

Fifteen Mile Stream gold deposit

A single sample of biotite was collected from this deposit area during reconnaissance field work in 1986. Sample FMS-86-3, collected from dump rock material in the vicinity of the old New Egerton workings, consists of a fine-grained, monomineralic clot of biotite located at the contact between a bedding-parallel quartz vein with crack-seal texture and pelitic wall rock. Because of the proximity of the biotite clot to the quartz vein, it is probable that the mica represents an alteration selvage to the vein and was contemporaneous with vein formation.

Moose River gold deposit

Two samples from the Moose River deposit were analyzed. One of these, ZMRM-1 muscovite, was collected by M. Zentilli in the mid 1970's from dump material in the vicinity of old scheelite workings of the deposit area. In this sample (M. Zentilli, personal communication, 1990) fine-grained sericite occurs as coatings and fracture fillings in massive, milky white, fragmented quartz that is crosscut by veinlets of medium to coarse, massive to euhedral scheelite. The second sample, MR-86-3, was collected during reconnaissance investigations of the deposit area in 1986 and also comes from the former scheelite producing part of the gold district. The sample is very similar to the previous one described except that the muscovite is coarser grained and the scheelite is more intimately grown with the massive, milky white quartz. Both samples of vein material are hosted by black pelitic wall rock.

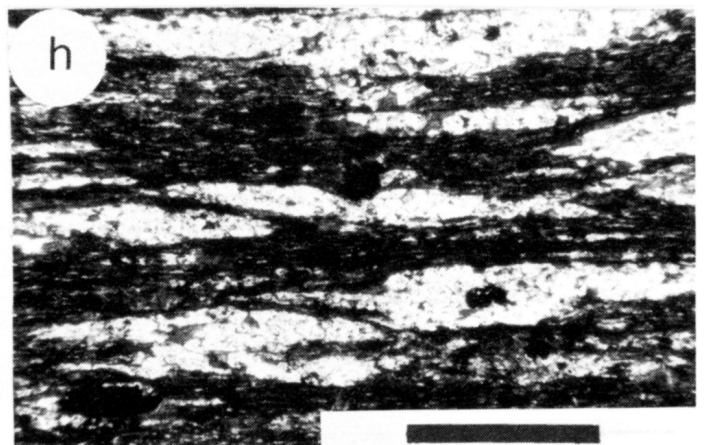
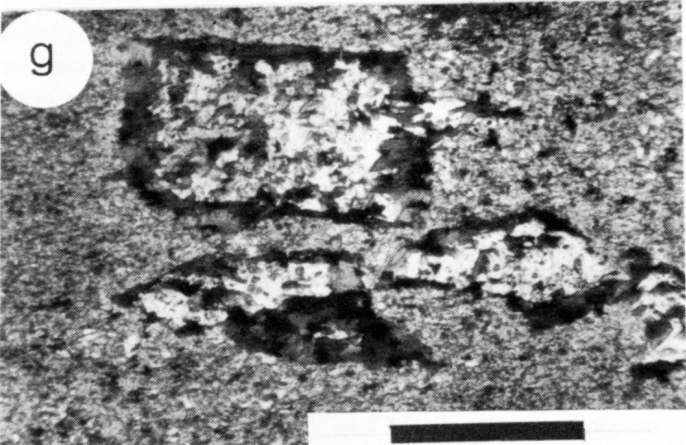
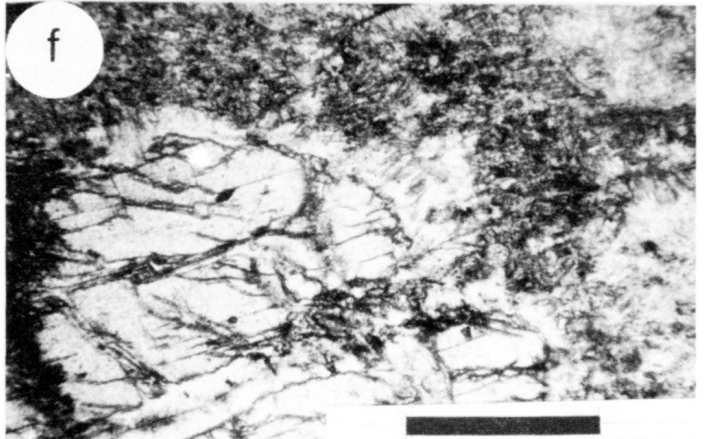
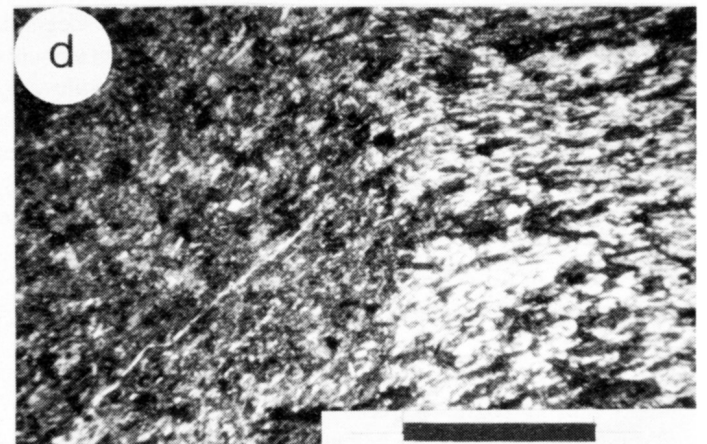
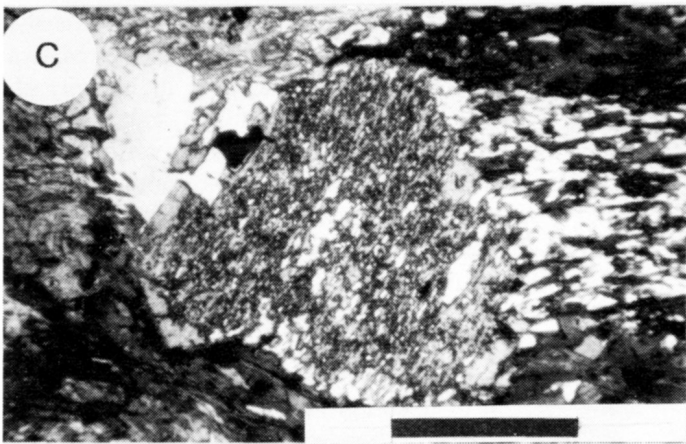
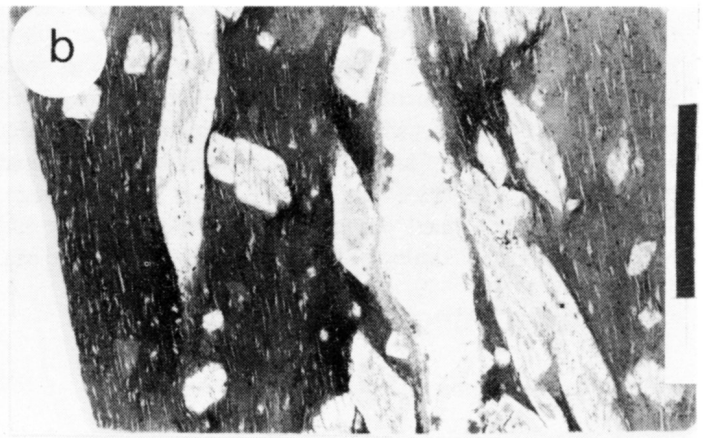
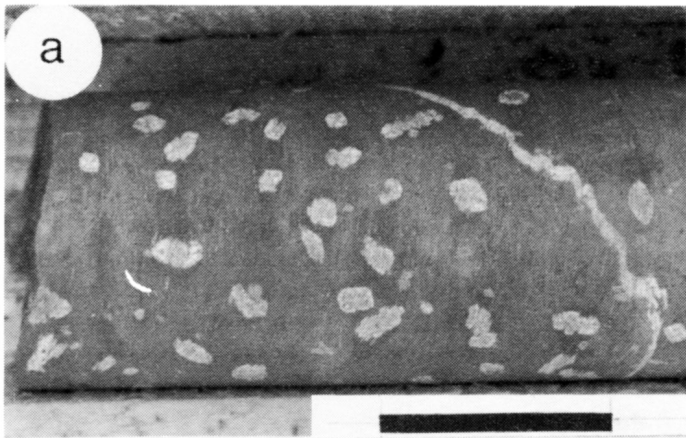
Upper Seal Harbour gold deposit

The Upper Seal Harbour gold district, located in the eastern part of the Meguma Terrane (Fig. 1), occurs in greenschist facies (biotite zone) greywackes of the Goldenville Formation along the apex of a closely folded anticlinal structure. The area is known for the tremendous thicknesses of milky white quartz material occupying the apex of the folded structure with stacking of these saddle-reef type veins (Malcolm, 1929). The greater part of the production from this area came from the Boston-Richardson mine workings.

A single sample from this locality was collected in the winter of 1989 from the new underground workings located about 40-50 m beneath the old Boston-Richardson workings. Sample USH-89-3 comes from a zone of massive, en echelon stockwork veins (total width 17 m) on the 250 level, approximately 30 m north of the main fold hinge. The mineral assemblage of quartz-carbonate-chlorite-plagioclase-muscovite is intergrown in a massive manner and for the most part appears to have precipitated simultaneously.

Analytical procedures

High quality mineral separates (i.e., >99%) were prepared using magnetic separation and heavy liquid techniques. The mineral separates, individually wrapped in thin aluminum foil



disks, were interspaced with six similarly wrapped monitors and stacked inside a cadmium-lined, aluminum canister and irradiated at the McMaster University nuclear reactor. The flux monitor used was the hornblende standard MMHb-1 which has an apparent K-Ar age of 519 Ma (Alexander *et al.*, 1978; Roddick, 1983). J-values derived from analysis of the flux monitors formed a linear array when plotted as a function of position in the canister and the appropriate J-value for each sample was obtained from the straight line fitted to these data (according to the method of York, 1969). Details of gas extraction and instrumentation are identical to the procedures in Reynolds *et al.* (1987). All ages have been calculated using the revised decay constants and isotopic abundance ratios recommended by Steiger and Jäger (1977). Age plateau is defined in Fleck *et al.* (1977). Errors (2 sigma) associated with the plateau ages are ca. 2-3 Ma and with the integrated ages ca. 3-4 Ma.

⁴⁰Ar/³⁹Ar results

The analytical data for samples from the Beaver Dam deposit area have been published elsewhere (Kontak *et al.*, in press-a); however, we also present and discuss here the age spectra for this locality. Results for the remaining samples are given in Table 2. The data are discussed separately for each deposit area first.

Beaver Dam gold deposit

Age spectra for 7 samples analyzed from the Beaver Dam area are presented in Figure 12. The results for a muscovite and biotite pair from the River Lake pluton (RL-86-1) indicate apparent plateau ages of 371.0 Ma and 378.8 Ma, respectively. The apparent reverse discordance noted for this sample (i.e., biotite older than muscovite) is unusual for granites of the Meguma Terrane, but Reynolds *et al.* (1981; Table 1) reported other such cases. Muscovite from the pegmatite/aplite segregation (NS-4S-86) has a well-defined plateau age of 371.0 Ma, indistinguishable from the plateau age obtained for the muscovite (RL-86-1) hosted by the granite.

Three hydrothermal biotites from quartz veins give apparent integrated ages ranging from 364 Ma to 373 Ma. For sample CX-86-6 a plateau age of 376 Ma is indicated, although calculation incorporates the slightly anomalous step at 900°C which indicates an apparent age of 380 Ma. If only the temperature fractions from 600°C to 850°C are used, incorporating some 57% of the gas released, then a plateau age of 374.5 Ma is calculated. For sample

BD-87-136 a prominent saddle appears in the middle of the age spectrum plot which may be an artifact of the irradiation procedure (i.e., recoil effect) related to incipient, submicroscopic chloritization of the biotite (e.g., Muecke *et al.*, 1988). If this part of the spectrum is dismissed, then an apparent plateau age of 374.2 Ma is calculated. Similarly, in BD-87-177 a slight discordance is noted due to a small hump in the middle of the age spectrum. An apparent plateau age of 367 Ma is calculated for this sample.

A single hydrothermal muscovite from the deposit area defines an apparent plateau age of 374 Ma for 74% of the gas released. The loss of data for one of the low temperature steps precludes calculation of an integrated age for this sample.

A single amphibole was analyzed and, although some analytical problems resulted in unusually large associated errors for individual steps, the plateau age of ca. 365 Ma is similar to the integrated age of 361 ± 16 Ma for this sample (Fig. 13b). Measured ³⁷Ar/³⁹Ar ratios, proportional to Ca/K, are relatively constant after the first 20% gas release and indicate that a chemically homogeneous phase has been analyzed, consistent with the electron microprobe analyses of this same mineral phase (Table 1). A ⁴⁰Ar/³⁶Ar versus ⁴⁰Ar/³⁹Ar isochron plot (Fig. 13c), regressed according to the method of York (1969), indicates an age of 367 ± 10 Ma (N=9, SUMS=17, MSWD=1.54), not significantly different from the plateau or integrated ages.

Caribou gold deposit

The two muscovites analyzed from the Caribou deposit (Fig. 14), CAR-88-23 and CAR-88-50, have apparent integrated ages of 367 Ma and 380 Ma, respectively. For sample CAR-88-23 the majority of the heating steps (94% of gas) indicate similar apparent ages, except for a single step with a relatively anomalously low apparent age of 345 Ma. If this latter step, probably an artifact of the analysis, is ignored, then an apparent plateau age calculated for the remaining spectrum is 373 Ma. In contrast, sample CAR-88-50 has a monotonic gradient beginning with the first step (600°C), which has an apparent age of 374 Ma, and gradually increasing to a maximum apparent age of 386 Ma (900°C).

Fifteen Mile Stream gold deposit

The single age spectrum for the biotite sample from the Fifteen Mile Stream deposit (Fig. 14) has an overall concave-shaped pattern with the middle portion, incorporating about 60%

Fig. 9. Photographs of drill core and thin sections for material from the Beaver Dam gold deposit area. (a) Drill core from the western extent of the deposit area showing euhedral andalusite porphyroblasts developed within a pelite. Note the presence of the folded quartz vein cutting the core. Bar scale 3 cm. (b) Photomicrograph of large thin section showing flattened, euhedra of chiasolitic andalusite in pelite. The subcircular dark spots are inclusion-rich cordierite porphyroblasts. Bar scale 2 cm. (c) Inclusion-rich, synkinematic staurolite grain in pelite. Bar scale 0.5 mm. (d) Inclusion-rich, synkinematic cordierite grain. Note the twin plane that transects the photograph. Bar scale 0.5 mm. (e) Drill core from the western extent of the deposit area showing partly flattened, subhedral andalusite grains cut by quartz ± carbonate veinlets. In detail the andalusites are observed to have been retrogressed to sericite. Bar scale 2 cm. (f) Photomicrograph showing remnant core of andalusite surrounded by fine-grained sericitic alteration product. Bar scale 0.5 mm. (g) Oikocrysts in pelite consisting of mostly quartz and biotite. Note that most of the biotite occurs along the margins and that these examples are of equant to subequant shape (contrast with next photomicrograph). Bar scale 0.5 mm. (h) Intensely deformed pelite containing quartz-rich oikocrysts that have been flattened to give large aspect ratios (compare with previous photomicrograph). Bar scale 0.5 mm.

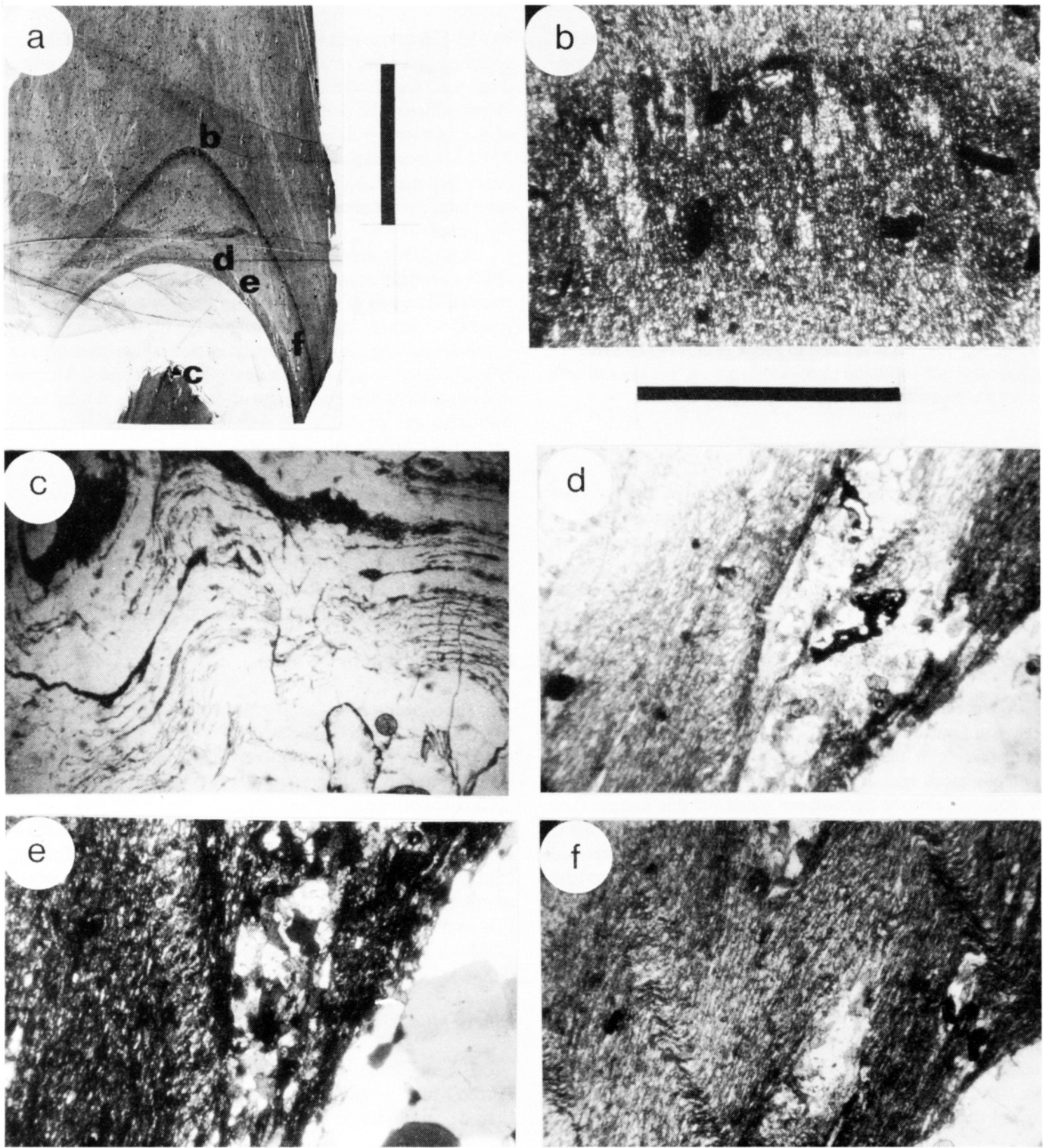


Fig. 10 Photomicrographs of folded quartz vein from the MEX pit, Beaver Dam gold deposit area. Bar scale for (a) is 2 cm and in the remained the bar scale is 1.0 mm. (a) Thin section showing folded quartz vein in pelite; note the following features: (1) presence of faint crack seal texture in the quartz vein that parallels the vein-wallrock contact. This is most obvious near the bottom of the vein (see photomicrograph in c); and (2) presence of oikocrysts throughout the pelite. The long dimension of the oikocrysts are parallel to the slaty cleavage in the rock. The letters refer to the locations of the subsequent photomicrographs. (b) matrix of the pelite showing the relationship between the slaty cleavage (subvertical) and bedding (subhorizontal). The faint white elliptical-shaped features are poorly developed oikocrysts. (c) Quartz vein showing the presence of crack seal texture. Note that the lamellae consist of residual wall rock material and not new mineral growth of dominantly mica (cf. Mawer, 1985, 1987). Also note that the lamellae are perpendicular to the slaty cleavage in the wallrock pelite. (d, e, f) Series of photomicrographs showing crenulation cleavage (S_2) which overprints an earlier subhorizontal cleavage (S_1). Note also that the oikocrysts are deformed by the later cleavage and that S_1 is essentially parallel to the wallrock-vein contact. These relationships indicate that the slaty cleavage observed in the pelite (e.g., Fig. 10b) is in fact the shear cleavage as discussed in the text.

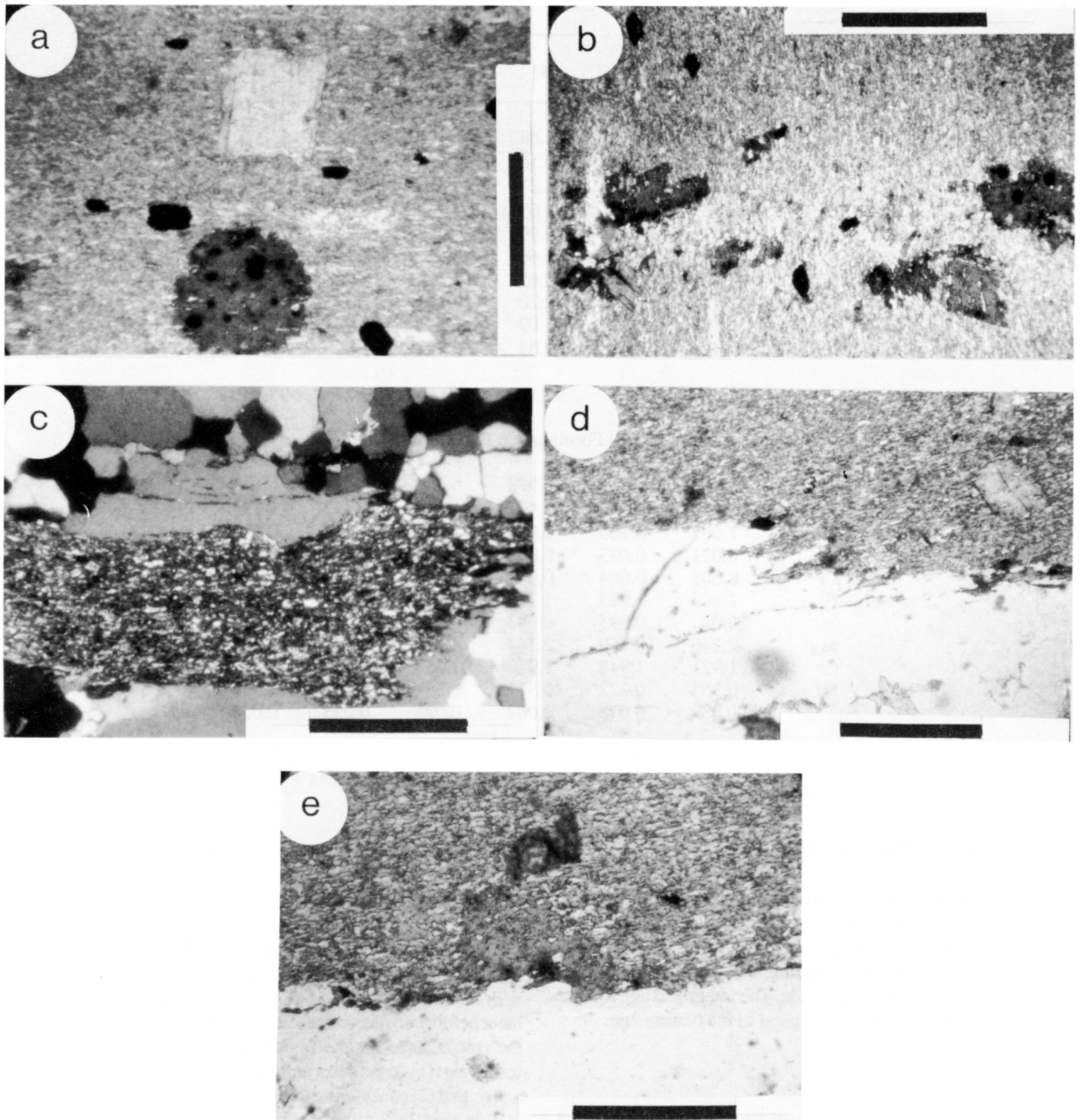


Fig. 11. Photomicrographs of vein and wall rock material from the Fifteen Mile Stream gold district. (a) Wall rock pelite showing biotite porphyroblasts overgrowing main fabric. Bar scale 0.4 mm. (b) Fracture in wall rock pelite with hydrothermal (?) biotite growing along it. Note also that the fracture crenulates the fabric. Bar scale 0.3 mm. (c) Inclusion of cleaved wall rock fragment in quartz vein with slight crack seal texture present. Note that the crack seal lamellae are parallel to the fabric in the sedimentary fragment. Bar scale 0.5 mm. (d) Thin septa of cleaved wall rock material extending into a quartz vein. Note the undeformed biotite porphyroblast overgrowing matrix in right side of photo. Bar scale 0.4 mm. (e) Biotite porphyroblast in wall rock pelite is truncated by quartz vein. Note that the biotite contains inclusion trails of matrix material. Bar scale 0.5 mm.

of the gas (steps 550°C to 850°C), defining an apparent plateau age of 362 Ma [note that the age plateau segment incorporates, but does not include in the calculation, the single step with the relatively low apparent age as it represents only 1% of the total

gas released (Fleck *et al.*, 1977)]. The 357 Ma integrated age for this sample is slightly younger than the plateau age due to tailing of the age spectrum in higher temperature steps.

Table 1. Electron microprobe analysis of amphibole (BD-87-61A).

Sample	1	3	4	5	9	10
SiO ₂	42.63	43.64	44.68	42.40	45.28	43.57
TiO ₂	0.19	0.30	0.16	0.13	0.12	0.08
Al ₂ O ₃	15.88	13.96	13.37	15.32	12.31	15.10
Cr ₂ O ₃	0.04	0.03	0.03	0.04	0.04	0.05
FeO	14.47	15.53	13.99	14.99	14.24	14.34
MnO	0.66	0.76	0.66	0.68	0.73	0.67
MgO	9.92	9.82	10.65	9.19	11.00	9.60
CaO	12.35	12.27	12.20	12.18	12.22	12.20
Na ₂ O	1.26	1.12	1.09	1.14	0.98	1.18
K ₂ O	0.48	0.41	0.33	0.50	0.29	0.44
Total	97.55	97.84	97.16	96.49	97.21	97.23
Structural Formulae on Basis of 23 O						
Si	6.350	6.467	6.598	6.356	6.688	6.770
Al ^(iv)	1.650	1.533	1.402	1.644	1.312	1.230
Al ^(vi)	1.067	0.905	0.926	1.064	0.832	0.872
Ti	0.021	0.033	0.018	0.015	0.013	0.018
Cr	0.005	0.004	0.004	0.005	0.005	0.007
Fe	1.803	1.925	1.728	1.879	1.759	1.703
Mn	0.084	0.095	0.083	0.086	0.091	0.084
Mg	2.146	2.169	2.344	2.053	2.422	2.396
Ca	1.921	1.948	1.930	1.957	1.934	1.922
Na	0.355	0.322	0.312	0.331	0.241	0.256
K	0.089	0.078	0.062	0.096	0.055	0.056

Analysis done at Dalhousie University, Halifax, Nova Scotia using a JEOL 733 Superprobe.

Upper Seal Harbour gold deposit

The single muscovite analyzed from the Upper Seal Harbour district (Fig. 14) has a slight hump in the initial part of the age spectra which includes about 12% of the gas released. Thereafter, a well-defined plateau incorporating 85% of the gas released indicates an apparent age of 366 Ma. The integrated age for this muscovite sample is 366 Ma, identical to the plateau age.

Moose River gold deposit

Muscovite ZMRM-1 has an integrated age of 374 Ma and a well-defined apparent plateau age of 375 Ma incorporating 93% of the gas released (Fig. 14). The second sample analyzed from Moose River, MR-86-9 (Fig. 14), has an integrated age of 379 Ma and well-defined plateau age of 380 Ma which incorporate 95% of the gas released. In both of the aforementioned samples, there is no apparent gradient defined as present, for example, in either slowly cooled or partially reheated samples (McDougall and Harrison, 1988).

DISCUSSION

Interpretation of the ⁴⁰Ar/³⁹Ar Age spectra

Results of the ⁴⁰Ar/³⁹Ar analyses indicate that the apparent ages for vein micas and amphibole range from 362 Ma to 382 Ma with the average ca. 370 Ma. However, points worthy of comment before conclusions can be drawn regarding the implications the results have for the timing of quartz veining include the following: (1) do the dates represent primary cooling ages or reset ages?; and (2) considering the spread of the data, spanning nearly 20 Ma duration, it is also important to consider if the dates represent discrete events, diachronous cooling or variable amounts of resetting.

Interpretation of data from the Beaver Dam deposit area

The results for the Beaver Dam area indicate a narrow spread of the age data of ca. 9 Ma, reflecting a thermal event of about 370 Ma which must have been $\geq 500^{\circ}\text{C}$, i.e., the temperature at which

Table 2. $^{40}\text{Ar}/^{39}\text{Ar}$ analytical data for samples from gold deposits.

Temperature (°C)	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{39}\text{Ar}/^{36}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{39}\text{Ar}_K$ (% Total)	$^{40}\text{Ar}_R$ %	Apparent Age (± 1 Ma)
CAR-88-50 Muscovite, Caribou Gold Deposit; J = 0.00245						
600	--	12.5	1476	2	80	374(3)
650	1.6	19.8	2184	3	86	379(2)
700	--	34.3	3529	7	92	375(1)
750	--	39.2	4057	10	93	380(1)
780	--	28.2	2992	9	90	379(1)
810	--	17.9	2028	7	85	382(1)
840	--	16.9	1922	8	85	382(1)
870	--	11.5	1407	6	79	381(1)
900	--	17.6	2015	12	85	386(1)
950	--	19.0	2144	13	86	384(1)
1000	--	14.5	1695	11	83	382(1)
1050	--	3.9	673	6	56	381(1)
1150	13	0.9	378	3	22	356(6)
CAR-88-23 Muscovite, Caribou Gold Deposit; J = 0.00245						
750	0.2	13.8	1596	12	81	373(1)
780	--	14.5	1662	5	82	373(1)
810	--	14.1	1617	8	82	372(1)
840	--	11.1	1252	12	76	345(2)
870	--	19.2	2083	9	86	370(1)
900	--	15.4	1740	10	83	372(1)
930	--	16.5	1841	8	84	372(1)
960	--	21.3	2313	19	87	376(1)
990	--	11.5	1373	11	78	371(1)
1020	--	2.2	436	1	32	257(17)
1050	--	2.0	62	3	28	363(3)
1140	--	0.4	326	1	9	309(24)
FMS-86-3 Biotite, Fifteen Mile Stream Gold Deposit; J = 0.00223						
500	--	5.9	726	2	60	273(3)
550	--	19.9	2081	4	86	330(2)
600	--	62.3	6472	14	95	361(1)
650	--	127.9	13074	20	98	364(1)
700	--	133.9	13644	15	98	363(1)
750	--	56	5847	7	95	361(1)
800	--	17.1	1955	1	85	353(3)
850	--	16.6	1957	4	85	364(1)
900	--	18.4	2067	8	86	351(1)
950	--	22	2473	10	88	360(1)
1000	--	11.7	1450	6	80	357(1)
1050	--	4.2	701	4	58	352(2)
1100	--	1.3	418	2	30	340(7)
USH-89-3 Muscovite, Upper Seal Harbour Gold Deposit; J = 0.00245						
600	0.3	10.6	1260	3	77	361(1)
650	--	29.4	3079	4	90	376(1)
700	--	49.5	4937	5	94	372(1)
750	--	50.8	4984	4	94	367(1)
780	--	53.9	5261	10	94	367(1)
810	--	7.9	995	9	70	352(2)
840	--	44.2	4362	16	93	366(1)

Apparent ages in 10^6 years. $^{39}\text{Ar}_K$ = ^{39}Ar derived from potassium as a consequence of the irradiation. $^{40}\text{Ar}_R$ = percentage of ^{40}Ar that is radiogenic.

Table 2 Cont. $^{40}\text{Ar}/^{39}\text{Ar}$ analytical data for samples from gold deposits.

Temperature (°C)	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{39}\text{Ar}/^{36}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{39}\text{Ar}_K$ (% Total)	$^{40}\text{Ar}_R$ %	Apparent Age (± 1 Ma)
USH-89-3 Muscovite, Upper Seal Harbour Gold Deposit; $J = 0.00245$						
870	--	31.7	3217	9	91	367(1)
900	--	44.6	4392	11	93	366(1)
950	--	33.5	3363	27	91	365(1)
1000	--	13.4	1521	6	81	364(1)
1050	--	2.0	476	3	38	352(2)
MR-86-9 Muscovite, Moose River Gold Deposit; $J = 0.0025$						
600	--	54.2	5689	4	95	364(1)
650	--	162.8	17209	9	98	379(10)
700	--	151.1	16022	10	98	379(10)
750	--	216.9	22937	13	99	381(1)
780	--	156.7	16657	12	98	381(1)
810	--	92.5	9952	8	97	380(1)
840	--	75.6	8179	6	96	380(1)
870	--	80.6	8720	8	97	381(1)
900	--	41.9	4681	5	94	381(1)
950	--	37.6	4218	7	93	380(1)
1000	--	36.2	4080	12	93	381(1)
1050	--	9.2	1260	5	77	380(1)
1100	--	0.8	373	1	21	349(12)
ZMRM-1 Muscovite, Moose River Gold Deposit; $J = 0.002766$						
500	0.3	2.7	515	2	43	330(9)
600	0.8	4	630	4	53	356(6)
700	--	9.1	1087	15	73	372(3)
800	--	56.7	5200	32	94	371(2)
900	--	42.4	3956	34	92	370(3)
1000	--	14.1	1502	13	80	367(3)

Apparent ages in 10^6 years.

$^{39}\text{Ar}_K = ^{39}\text{Ar}$ derived from potassium as a consequence of the irradiation.

$^{40}\text{Ar}_R =$ percentage of ^{40}Ar that is radiogenic.

amphibole closes with respect to Ar diffusion (Harrison, 1981). In addition, concordancy of the mineral dates predicates that the area must have cooled rapidly following crystallization of these vein constituents because the collective range of Ar diffusion in these minerals is about 250°C (Harrison, 1981; Harrison *et al.*, 1985; Harrison and McDougall, 1980a, b and references therein). However, the difficult question which remains is whether this cooling event reflects a primary or secondary thermal event considering the proximity of the nearby River Lake pluton and the coincidence of the ages obtained with the time of granitic intrusion in the Meguma Terrane. In order to address this point, three issues must be considered, namely (1) the geological features of the deposit area, (2) analogy to other geochronological studies in contact metamorphic environments, and (3) comparison to theoretical models for cooling plutons and their country rock environments.

The geological features of the Beaver Dam deposit area are wholly consistent with a single hydrothermal event rather than

multiple episodes of veining and/or thermal pulses over a protracted time interval. The following mineralogical, isotopic and fluid inclusion data (see Kontak *et al.*, 1988a, 1988b; Kontak and Smith, 1988, 1989) are considered to mitigate against a reheating episode which presumably would involve the participation of a fluid phase: (1) normal zoning profiles (i.e., microprobe data) in vein minerals (plagioclase, garnet, tourmaline) would not survive reheating to temperatures $\geq 500^\circ\text{C}$; (2) the presence of coexisting chlorite-carbonate-muscovite-plagioclase-biotite and amphibole-epidote-biotite-carbonate-chlorite assemblages with the absence of any prograde reactions; (3) a simple mineral paragenesis involving an initial high temperature stage succeeded by a later, lower temperature stage (e.g., Fig. 2); (4) presence of fluid inclusions representing a single fluid event. No evidence has been found to suggest passage of a second, high temperature fluid; (5) a narrow range for all stable isotopic data (S, C, O) which, although not inconsistent with the passage of a second fluid phase, would require a coincident set of physical and

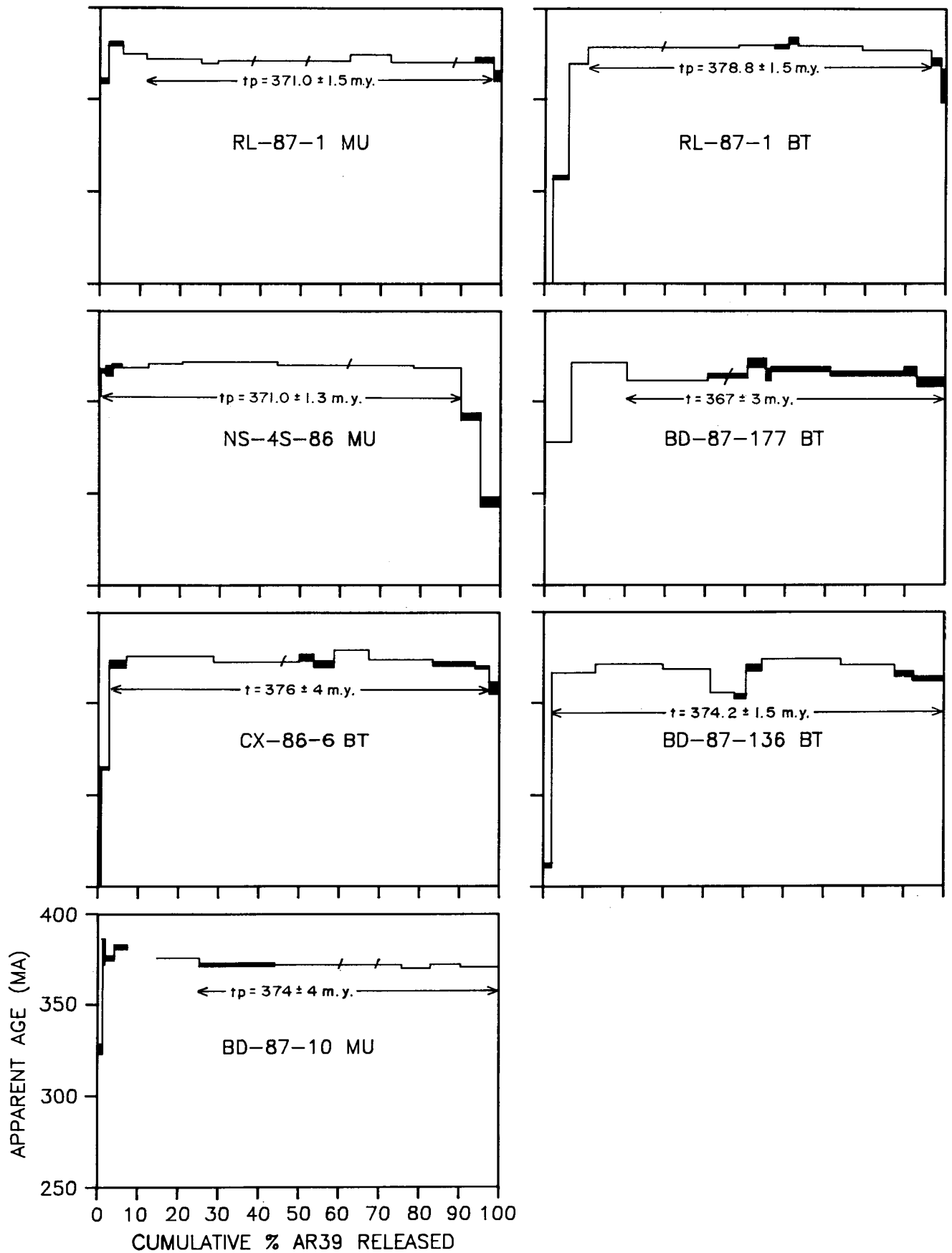


Fig. 12. Incremental release age spectrum diagrams for mineral separates (BT - biotite, MU - muscovite) from the River Lake pluton (RL-87-1) and associated pegmatite/aplite (NS-4S-86), and Beaver Dam gold deposit area (all other samples). The vertical and horizontal scales are the same on each age spectrum plot. Complete results are available in Kontak *et al.* (in press-a).

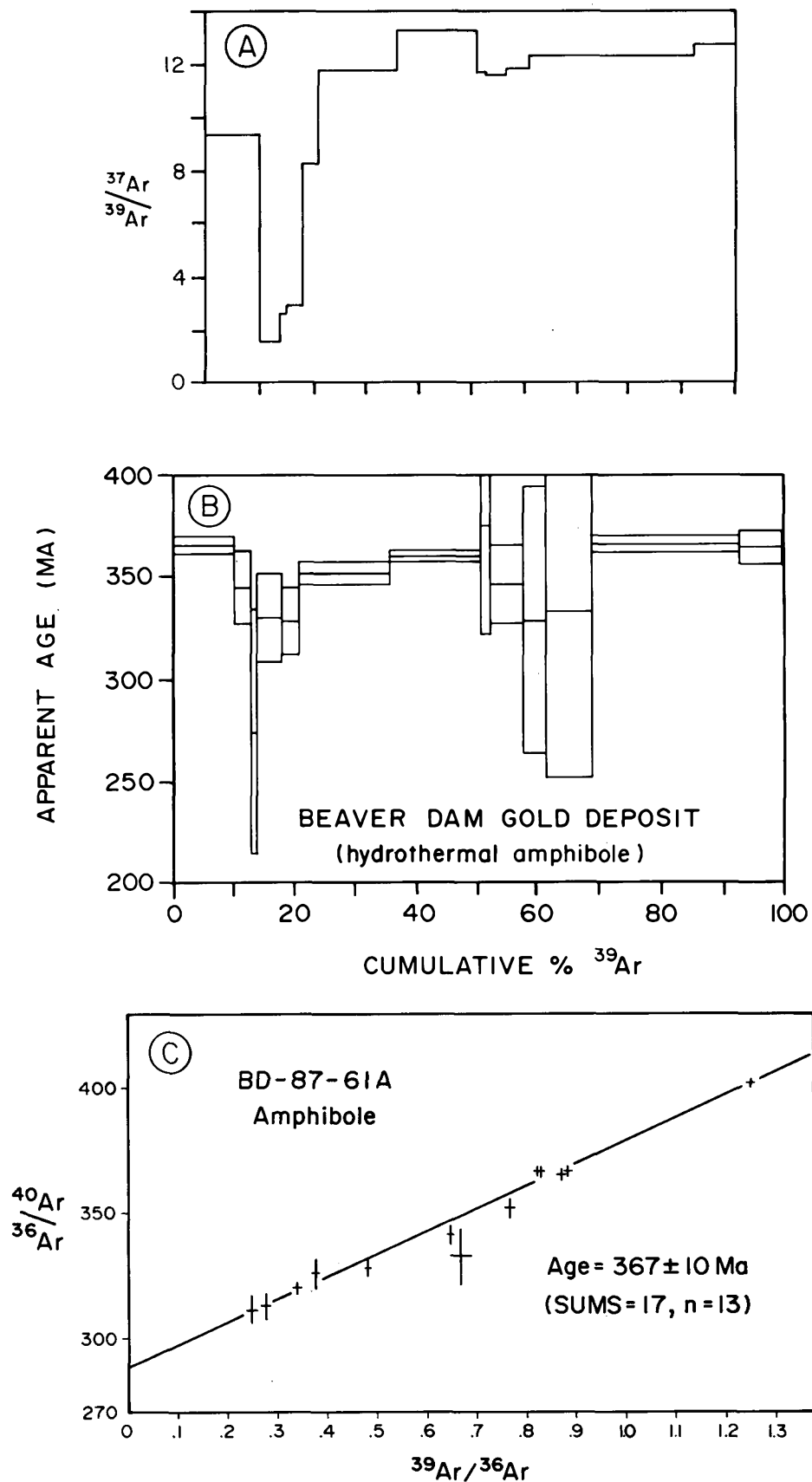


Fig. 13. Ar data for amphibole sample BD-87-61A from the Beaver Dam deposit. (a) $^{37}\text{Ar}/^{39}\text{Ar}$ versus cumulative % ^{39}Ar plot for amphibole sample. This plot is proportional to the Ca/K ratio of the phase being outgassed at each incremental temperature step; (b) incremental release age spectrum plot for amphibole sample; (c) $^{40}\text{Ar}/^{36}\text{Ar}$ versus $^{39}\text{Ar}/^{36}\text{Ar}$ isochron plot for amphibole sample. Note that the associated statistics of SUMS=17 for n=13, or equivalent MSWD=1.54, indicate that the data define an isochron.

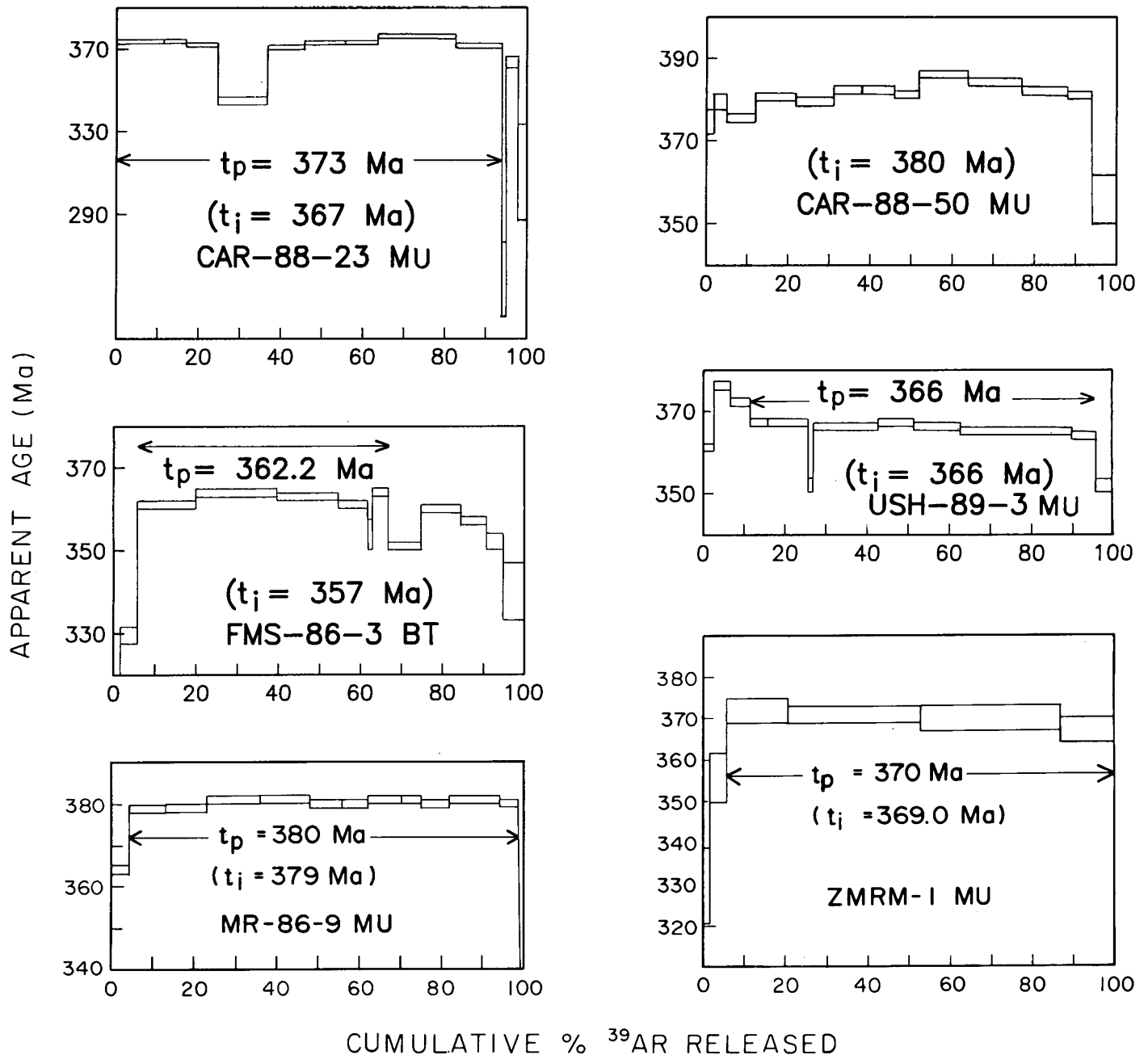


Fig. 14. Incremental release age spectrum diagrams for mineral separates (BT - biotite, MU - muscovite) from Caribou (CAR), Upper Seal Harbour (USH), Moose River (MR, ZMRM) and Fifteen Mile Stream (FMS) gold districts. Complete results are available in Table 2.

chemical parameters; and (6) vein micas (biotite, muscovite, chlorite) have very consistent chemistries; although this is not inconsistent with a second hydrothermal event it would require similar physical and chemical conditions to once again prevail.

The classical geochronological studies of Hart (1964) and Berger (1975), which focused on the thermal overprinting of minerals in the contact metamorphic aureole of the Eldora stock, Colorado, are especially applicable to the present investigation. These workers dated biotite, K-feldspar and amphibole by the K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ techniques from gneiss of the Precambrian country rocks, both from outside and within the thermal influence of the ca. 56 Ma Eldora stock. Of relevance to this study are the following observations extracted from their work: (1) the dimen-

sions of the Eldora stock are similar to the River Lake pluton, thus the magnitude of the thermal disturbance should be similar in the two cases; (2) K-Ar ages of amphibole are relatively unaffected beyond the first 33 m and the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for samples 41 m and 75 m removed from the contact define excellent plateau ages (i.e., define an older, Precambrian metamorphic event that affected the country rock) with no diffusion profiles detected for low temperature gas fractions; (3) biotite samples from >1575 m from the contact give unaffected $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra while those 7 m away are totally reset to 56 Ma; samples from intermediate distances give variably disturbed age spectra; and (4) Hart (1964) also noted a change in the color of biotite commensurate with rutilization of the host as a result of the thermal disturbance. This

textural feature was noted in samples collected as far as 1 km from the contact.

Also applicable to the present investigation is the detailed geochronological study conducted by Harrison and McDougall (1980a, b) on the thermal history of the Separation Point batholith and immediate country rock. Of particular importance here is the analysis of argon diffusion in amphiboles from the country rock gabbro. These authors showed that diffusion profiles, similar to those predicted by the volume diffusion model of Turner (1968), characterize amphiboles from within the influence of the thermal aureole of the batholith. Although the size of the batholith (>100 km in length) is such that direct analogy to the present study is at best only an approximation, it is worth noting that amphiboles from 0.3, 1.0 and 2.5 km from the contact show discordant profiles.

The studies of the Eldora stock and Separation Point batholith have direct application to the data from the Beaver Dam area. Comparison with the results reviewed above indicates no apparent reason to interpret the data from the Beaver Dam area as representing resetting. For example, (1) there is no rutilization of any biotite, (2) volume-type diffusion profiles are absent in all mineral phases, (3) all the biotites analyzed give the same age despite one of these (CX-86-6) coming from 1 km closer to the River Lake pluton than the other two, and (4) concordancy of the biotite, muscovite and amphibole dates which contrasts with the results for the Eldora stock study in which such concordant ages were only obtained within the contact aureole immediately adjacent to the intrusion (i.e., within a few metres of the contact).

The third point to consider is the constraint imposed by theoretical heat flow models. In such models one must first consider the mechanism of cooling, that is whether heat is conducted via convective or conductive processes. The former process is generally detected using stable isotope data (e.g., Taylor, 1977, 1978) that indicates incursion of isotopically light meteoric water as part of a fossil hydrothermal system around cooling plutons. The uniform $\delta^{18}\text{O}$ isotopic signatures of granites in the Meguma Terrane (Longstaffe *et al.*, 1980; Kontak *et al.*, 1988e; O'Reilly, 1988b) with $\delta^{18}\text{O}$ values of +9 to 11 ‰ indicate that the intrusions behaved essentially as closed systems. Although such data are not available for the River Lake pluton, stable isotope data for vein material from the Beaver Dam deposit area (Kontak *et al.*, 1988b) indicate that meteoric waters were not present at this structural level. Thus, the River Lake intrusion is considered to have cooled conductively. Cooling of intrusions and their thermal aureoles in such situations has been modelled by, among others, Hart (1964), Kerrick (1987) and Paramentier and Schedl (1981). Figure 15 is a diagram applicable to conductively cooled intrusions which relates the maximum temperature obtained in the country rock to various distances from the contact. If reasonable parameters for size, depth (see Thomas, 1982), ambient temperature of the country rock (200-250°C) and distance below the roof of the intrusion ($S = 0.4R$ in this case) are used, then maximum temperatures for the country rock, assuming a contact temperature of 650°C, are 440°C and 375°C for 1 and 2 km distances, respectively. Note that if a smaller value of S is used, which is probable according to Thomas (1982), then these maximum temperatures would decrease dra-

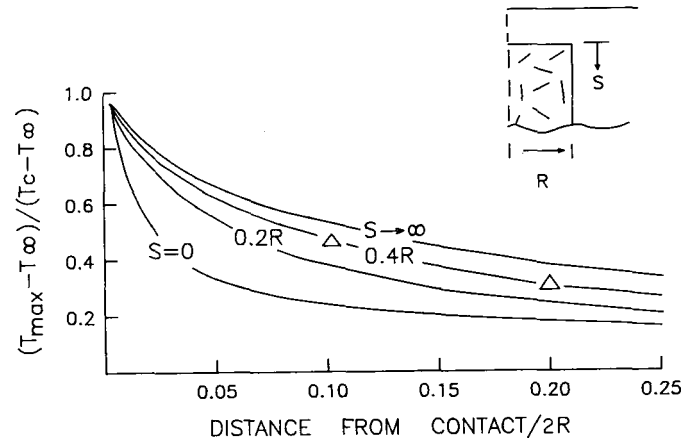


Fig. 15. Plot of maximum temperature (T_{max}) attained in the country rock of a conductively cooled intrusion as a function of distance from the contact. The curves shown are for a cylindrical-shaped intrusion at several depths below the top of the intrusive body. Abbreviations: T - country rock temperature far from the intrusion, T_c - initial contact temperature, R - radius of the intrusion, S - distance beneath top of the intrusion. Note that calculations used in the text are for $S = 0.4R$ ($R = 5$ km) at 1 and 2 km distance from the contact (indicated by the triangles on the appropriate curve). Diagram modified from Figure 5 of Paramentier and Schedl (1981).

matically. Hence, the limitation implied from the thermal modelling, assuming conductive cooling, is that the maximum temperatures that might have been generated at the Beaver Dam deposit due to intrusion of the River Lake granite are at best 350-375°C. Such temperatures are not sufficient to cause removal of Ar from amphibole due to thermally activated diffusion processes.

The foregoing discussion strongly favors interpretation of the $^{40}\text{Ar}/^{39}\text{Ar}$ data from Beaver Dam to represent a single hydrothermal event of ca. 370 Ma age. The ages do not reflect an overprinting event and the concordancy of the data from different minerals implies rapid post-crystallization cooling through the respective blocking temperatures of the analyzed mineral phases.

Interpretation of data from other gold deposit areas

Interpretation of the remaining data is more tenuous because fewer determinations have been made (total of 6 analyses for 4 deposits). However, points to be considered are as follows: (1) the range of ages from ca. 380 Ma to ca. 362 Ma; (2) the distances that the deposit areas are from intrusions; and (3) the timing of regional metamorphism and granite intrusion.

The spread of the ages obtained is statistically meaningful and implies, therefore, that vein formation occurred over a protracted time interval. Examination of available geological and gradiometry maps for the eastern Meguma Terrane indicates that none of the areas of concern occurs within the influence of a granite. The worst case scenario is Fifteen Mile Stream where the eastern lobe of the Liscomb Complex is ca. 5 km distant. Thus, for the same reasons as discussed for the Beaver Dam data it is considered unlikely that the ages reflect updating due to contact metamorphism. An additional point worth noting is that the older

ages of ca. 375-380 Ma for the Caribou and Moose River deposits exceed both $^{40}\text{Ar}/^{39}\text{Ar}$ mica (Fig. 16) and U/Pb zircon and monazite (Krogh and Keppie, 1988) ages for granites of the eastern Meguma Terrane. In contrast, mica porphyroblasts of contact metamorphic origin analyzed by Keppie and Dallmeyer (1987) give ages corresponding to the average age obtained for the granites (Fig. 16). The geochronological data summarized in Figure 16 also indicate that the ages obtained for the gold deposits post-date the age of regional metamorphism. Additional work on the age of regional metamorphism in the western Meguma Terrane indicates a similar age for this event (Reynolds and Muecke, 1978; Muecke *et al.*, 1988).

Timing of quartz vein formation in the Meguma Group

The foregoing discussion indicates that there is ample reason to interpret the ages obtained for vein minerals as representing primary cooling ages. Hence, the time of quartz vein formation

in the deposit areas examined is concluded to have occurred over a protracted time interval that spanned the termination of the regional Acadian Orogeny, as presently constrained geochronologically, and generation and emplacement of the granite intrusions. The data from Beaver Dam suggest that cooling of the deposit areas occurred rapidly following vein emplacement and, therefore, that the difference in ages among the gold districts is not related to diachronous cooling. Instead, discrete pulses of hydrothermal activity are inferred to have occurred.

The conclusions derived from our geochronological studies are compatible with the geological constraints discussed above. The veins in many cases occupy late structural sites (e.g., Mount Uniacke, Caribou) and in many cases petrofabric studies indicate that veins post-dated formation of the regional Acadian cleavage. Our earlier inference that the gold districts are localized to zones of high strain or shear belts (Kontak *et al.*, 1990b) is consistent with the data presented herein.

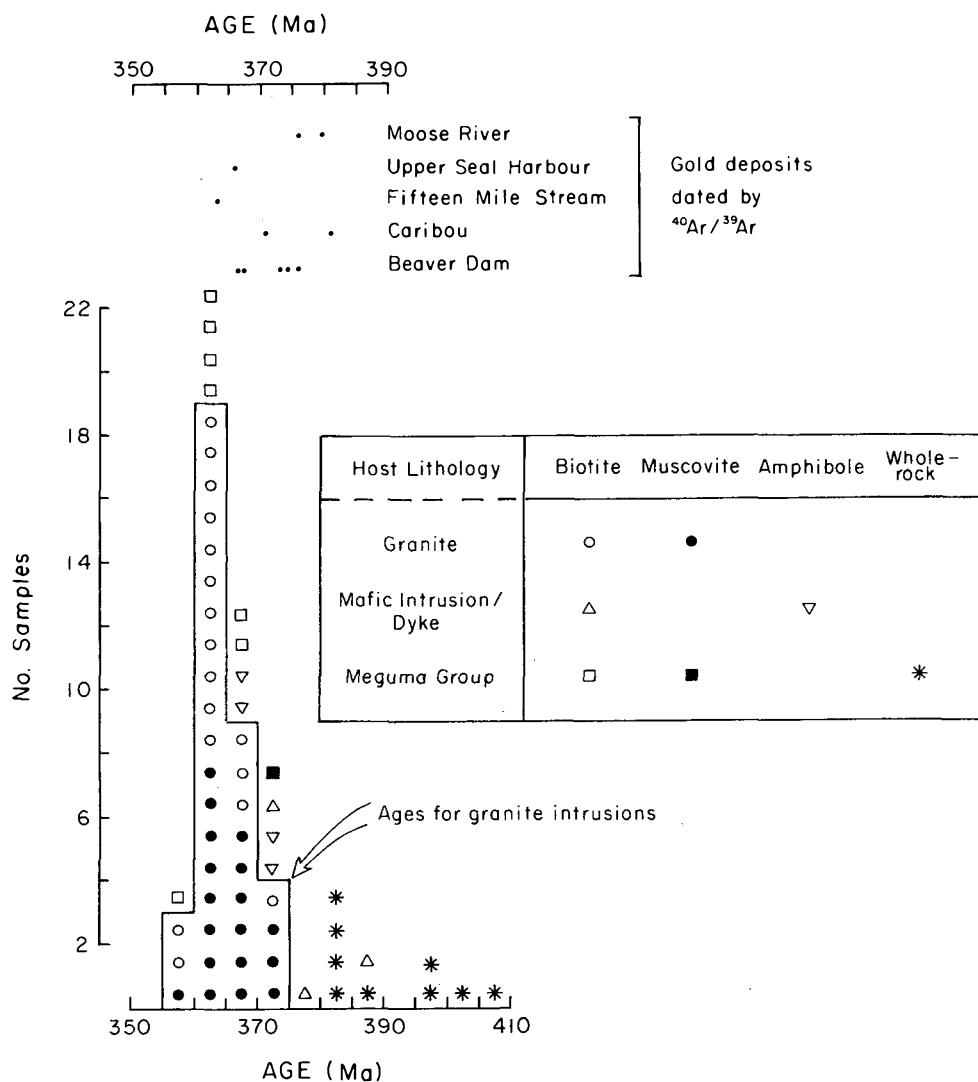


Fig. 16. Histogram plot of $^{40}\text{Ar}/^{39}\text{Ar}$ ages for granites, mafic intrusions and Meguma Group metasedimentary rocks in the eastern Meguma Terrane. Sources of data: Reynolds *et al.* (1981), Keppie and Dallmeyer (1987), Kempster *et al.* (1989), Kontak *et al.* (1989a, 1990a). Ages for the gold deposits are from this study. Note that in addition to the ages shown, Krogh and Keppie (1988) reported U/Pb zircon and monazite ages of ca. 372 Ma for the Larrys River and Halfway Cove plutons of the eastern Meguma Terrane.

Implications for genetic models for Meguma Group lode-gold deposits

The inferred timing of quartz vein formation of ca. 362-380 Ma has important implications with respect to genetic models proposed for the Meguma gold deposits. The timing of vein formation determined in this study clearly indicates an age that post-dates regional metamorphism and deformation of the host Meguma Group. Hence, models that invoke lateral secretion-type processes concurrent with regional tectonism are invalidated, as are models which have vein formation predating the regional folding event. Similarly, the fact that the ages of some deposit areas apparently predate granite emplacement indicates that a direct genetic connection to these intrusions is not possible in all cases.

The age data would be most compatible with models that permit continued formation or reactivation of regional structures (e.g., shear zones) as a consequence of progressive deformation of the Meguma Terrane. That such processes were operative during Late Devonian to Early Carboniferous time has been demonstrated by numerous workers (e.g., Mawer and White, 1986; Keppie and Dallmeyer, 1987; Horne *et al.*, 1988; Kontak and Cormier, in press) in response to continued transpression of the Meguma Terrane after initial emplacement along the Cobequid-Chedabucto Fault System. The ultimate origin of the fluids responsible for vein formation remains ambiguous, although their dominantly metamorphic nature is firmly established (e.g., Kontak *et al.*, 1988b; Kontak and Smith, 1989). As discussed elsewhere (Kontak *et al.*, 1990b), we favor a dynamic model which incorporates the influence of regional tectonic processes that converged during Late Devonian time as a consequence of protracted deformation of the Meguma Terrane, underplating of the same terrane by mafic magma (e.g., gabbros of the Liscomb Complex) and large scale anatexis of the Meguma Group infrastructure to generate the peraluminous granites.

CONCLUSIONS

Geological and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data for Meguma gold deposits within the eastern Meguma Terrane (Caribou, Beaver Dam, Fifteen Mile Stream, Upper Seal Harbour, Moose River, Mooseland) indicate that the timing of quartz vein formation post-dated the regional Acadian Orogeny of ca. 400 ± 10 Ma age. In some districts field relationships and petrographic observations provide a relative time frame such that vein formation was synchronous with crenulation of an earlier, regional cleavage (S_1). In addition, in areas proximal to 370 Ma granite intrusions, the alteration and deformation of hornfels adjacent to quartz veins provide a maximum time of vein formation (i.e., 370 Ma). Finally, the nature of some ore zones (e.g., Caribou, Mount Uniacke) indicates that vein formation followed regional deformation and folding (F_1) because the ore zones crosscut anticlines and occupy late structural sites.

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of vein constituents (amphibole, micas) give ages that range from ca. 380 Ma to ca. 362 Ma. Although variables such as resetting by granites and regional scale diachronous cooling are considered, the data are interpreted to reflect the

time of primary cooling through respective blocking temperatures for Ar diffusion. Thus, the concordance of amphibole, muscovite and biotite ages of ca. 370 Ma for the Beaver Dam deposit area indicate rapid cooling following vein formation. The collective range of ages (380 Ma to 362 Ma) for the deposits dated indicates that vein formation was a protracted event. Comparison to available geochronological data for regional metamorphism and granite emplacement within the eastern Meguma Terrane indicates that vein formation was essentially intermediate between these two events, although in part overlapping $^{40}\text{Ar}/^{39}\text{Ar}$ mica ages for granites.

The data indicate that models proposed for the Meguma gold deposits which invoke vein formation pre- or syn-regional deformation and metamorphism are invalidated; similarly, models which have genetic ties to the granites cannot accommodate the range of ages for deposit formation. The favored model is a dynamic one that encompasses the continued deformation of the Meguma Terrane during late Devonian time as a result of continued transpression of this terrane after its initial docking. This deformation was accompanied by widespread generation of metamorphic fluids as a consequence of underplating of the crust by ponded, mafic magma and large scale anatexis and generation of peraluminous melts.

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