The Coxheath Plutonic-Volcanic Belt (NTS 11K/01): A Linked Porphyry-Epithermal Mineralized System of Precambrian Age

D. J. Kontak, J. DeWolfe[1] and P. W. Finck

Introduction

Porphyry-type mineral deposits typically occur in Mesozoic and younger, calc-alkaline to alkaline volcanic-plutonic terranes formed predominantly at convergent plate margins (Sillitoe, 1976; Mitchell and Garson, 1981; Titley and Beane, 1981). These deposits are important repositories for Cu, Mo and Au, and account for a significant proportion of the total global resources. Presently the Cu-Au deposit types are amongst the most sought-after exploration targets given their large size, precious-metal endowment and cost-efficient open pit mining technique. The high-level nature of these mineralized systems, generally within the volcanic pile or the underlying, coeval plutonic environment (Sillitoe, 1973; Titley and Beane, 1981), is susceptible to rapid denudation in active orogenic belts, hence the likelihood of preservation in ancient terranes is considered poor, although rarely reported (Gustafson and Titley, 1978). Thus it is somewhat anomalous that inferred porphyry-type mineral occurrences older than Mesozoic age are reported in a number of locations in the northern Appalachians. More than ten porphyry-type systems have been reported in eastern Canada, including Gaspe Copper in eastern Quebec, Benjamin River in New Brunswick, and Coxheath in Nova Scotia (Hollister *et al.,* 1974; Kirkham and Soregaroli, 1975). The Coxheath deposit is even more anomalous given the ca. 620 Ma age for the host rock (Barr *et al.,* 1996).

In the present paper the results of previous work on the Coxheath Cu-Mo-Au deposit (Kontak *et al.,* 2000; DeWolfe, 2000) are integrated with recent investigations of previously known pyrophyllite occurrences in the northern part of the Coxheath Group volcanic rocks. The presence of pyrophyllite in volcanic rocks is common in high-sulphidization, epithermal base- and precious-metal deposits (White and Hedenquist, 1995), which themselves may be linked to an underlying porphyry system (Hedenquist et al., 1998). Thus, this paper explores the possibility that these spatially associated pyrophyllite occurrences are in fact the high-level manifestation of a genetically linked porphyry system at depth. The present distribution of the spatially and temporally related plutonic-volcanic rocks of the Coxheath belt suggest that this mineralized environment may represent a section through a porphyry environment, perhaps analogous to the large Yerington, Nevada, porphyry system exposed in a 6 km section because of post-emplacement tilting (Dilles and Einaudi, 1992).

Previous Work

Copper was first reported in the Coxheath Hills area in 1875 by Hugh Fletcher of the Geological Survey of Canada in his report on the Sydney coal fields. Subsequently high-grade copper was found in a shear zone along Copper Creek (Mine Zone) near where the number 2 shaft was put down. Most of the mine development occurred from 1881-1889 when five shafts were sunk and trenches and adits cut, and again in 1928-1930 when the shafts and drifts were further developed and a new zone explored (Mountain Zone). Most of the ore (to 3-10% Cu) extracted from the mine came from four sub-parallel shear zones known as the B, C, D and LW veins. The number 2 shaft was dewatered in 1947 and two levels (260, 340) were partially sampled by the Nova Scotia Department of Mines in order to assess its potential. A resource of

[1]Department of Earth Sciences and Mineral Exploration Research Centre (MERC), Laurentian University, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5

ca. 100,000 tons of 3% Cu was estimated to occur from the 340 level to surface. Later development and exploration delineated several other low-grade copper ore zones, and in 1964 Mariner Mines Ltd. discovered molybdenum in granitoid rocks of the Central Zone. This latter discovery changed the concept of the deposit from that of a high-grade, small-tonnage copper prospect to that of a potentially large-tonnage, lower-grade porphyry system (Chatterjee and Oldale, 1980). Moreover, the work of Mariner Mines and others over the past few decades has firmly established the potential for a large-tonnage, low-grade porphyry deposit with representative multi-metre intervals carrying 0.5 to 1.5% Cu with 1-5 g/t Au and molybdenum intercepts of about 1% Mo over 2 m and 0.3% over 16 m (Chatterjee and Oldale, 1980; L. Jensen, personal communication, 2001).

The mineralized area has been examined by several workers, all of whom have noted the similarities with porphyry-style mineralization (Hollister *et al.,* 1974; Kirkham and Soregaroli, 1975; Chatterjee and Oldale, 1980; Lynch and Ortega, 1997; DeWolfe, 2000). Most recently, Ortega and Lynch (1994a, b) mapped out a large, zoned alteration pattern in the plutonic-volcanic rocks that is similar to the alteration sequence present in typical porphyry systems (Lowell and Guilbert, 1970). Lynch and Ortega (1997) discussed the nature of the ore assemblage, alteration and nature of the tourmaline alteration in the Coxheath deposit and drew analogues with large porphyry-epithermal systems where similar alteration occurs. Furthermore, these authors also recognized the strong similarities of the Coxheath system to Au-bearing porphyries, noting the disseminated nature of the Au, the association with Cu, presence of sodic and calcic alteration in the mineralized environment, and pervasive propylitic alteration (Sillitoe, 1993).

Regional Geological Setting

The Coxheath plutonic-volcanic belt (CPVB) occurs in eastern Cape Breton Island and is the westernmost of several Late Precambrian (i.e. Hadrynian) volcanic-plutonic belts that together form part of the Avalon Terrane of the Canadian Appalachians. These belts, from the Atlantic

coastline in the east to the Bras d'Or Lakes in the west, are the Coastal Belt (570 Ma), Stirling Belt (680 Ma), Sporting Mountain Belt (620 Ma), East Bay Hills Belt (620 Ma), and Coxheath Belt (620 Ma). Based on the petrological features of the igneous rock suites, these belts are considered to represent the remnants of once extensive continental margin plutonic-volcanic arcs that formed above ancient, westward-dipping, subduction zones (e.g. Keppie and Dostal, 1991). Thus, these belts may be considered ancient analogues of the Andean-type continental margin tectonics where numerous porphyry deposits are located. The rocks form basement blocks that define prominent topographic highs surrounded by younger Cambrian to Carboniferous sedimentary rocks. Within these rocks are variable amounts of polymetallic mineralization that correlate in terms of metal endowment and style with porphyry (e.g. Coxheath) and massive sulphide (VHMS; Stirling) types of deposits.

The Coxheath Group of the CPVB underlies the Coxheath Hills and Spruce Brook areas on the north side of East Bay and is divided into three lithological units of basaltic, andesitic and rhyolitic composition. Each unit contains both flows and fragmental rocks, but epiclastic sedimentary rocks are rare. The volcanic rocks were intruded by dioritic to granitic rocks. The rocks have been metamorphosed to greenschist or sub-greenschist facies and have a weak, northeast-trending fabric with steep dips. Poles to primary layering in the volcanic rocks suggest folding about a southwest-plunging axis. The volcanic and plutonic rocks are overlain unconformably by Cambrian to Carboniferous sedimentary rocks.

Geological Features of the Coxheath Deposit

The geology of the two relevant areas of this study, namely the Coxheath Cu-Mo-Au mineralized system and the pyrophyllite-altered felsic volcanic rocks (Fig. 1), are described separately below. Subsequently the two areas are integrated into a genetic model which links them as part of a porphyry, high-sulphidization epithermal system. A more complete description of the Coxheath area is
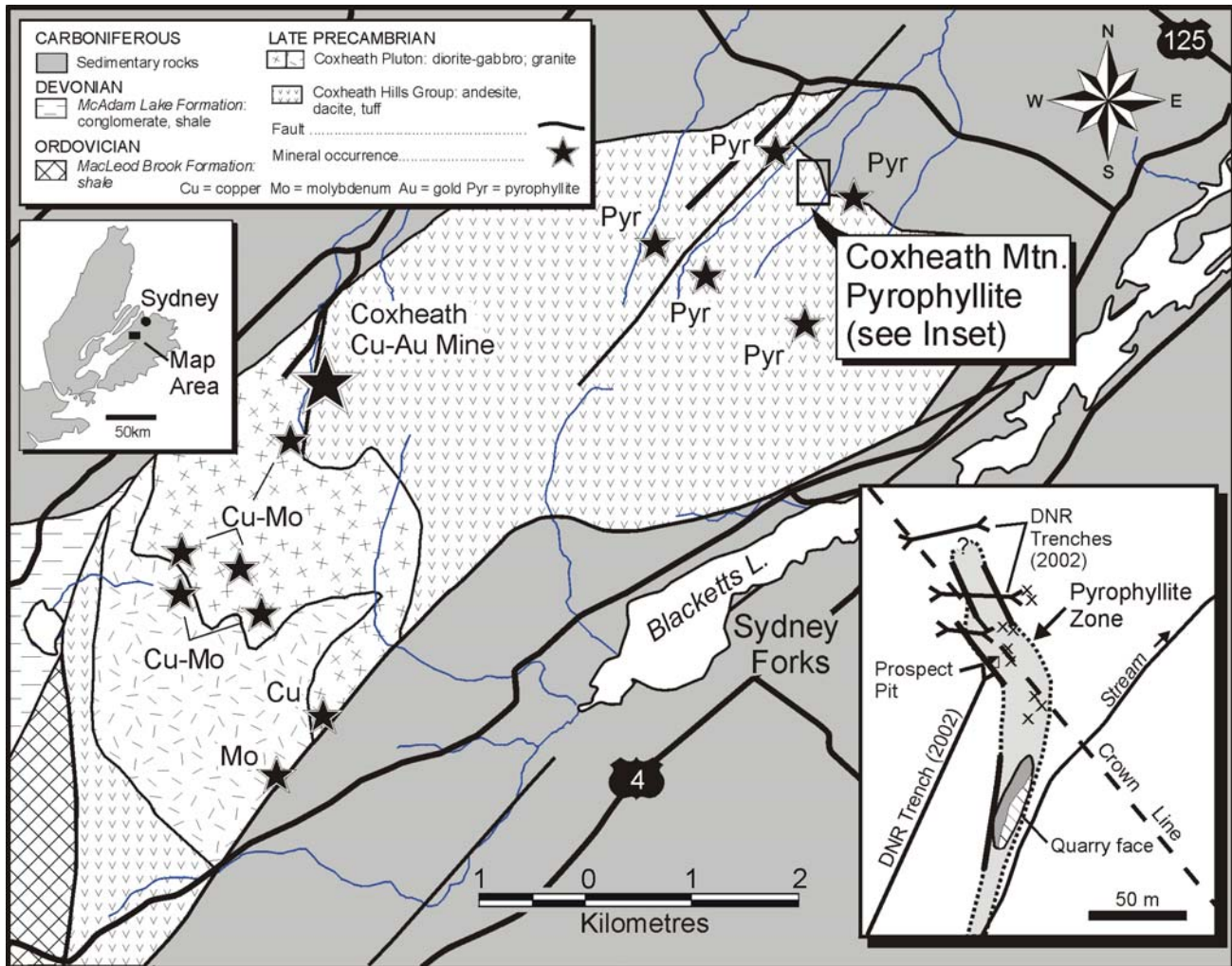
Figure 1. Regional geological setting of the Coxheath area showing the location of the Coxheath deposit and related mineralized zones, and the areas of pyrophyllite mineralization. Inset box is enlargement of the area of trenching done by NSDNR in fall of 2002.

in preparation (Kontak and Dewolfe, in prep.) and what follows is a brief description of a more comprehensive database.

Petrology of the Plutonic and Volcanic Rocks of the Coxheath Deposit Area

The Coxheath deposit occurs within a medium- to fine-grained hornblende diorite pluton that intrudes a volcanic carapace of basalt and basaltic andesite.

More felsic rocks occur distally from the Coxheath deposit area toward the northeast. The medium-grained phase can be followed upward, that is toward higher exposed levels topographically, into a much finer-grained equivalent. In one place in the southwest end of the Coxheath quarry[1], the diorite is chilled over 20 cm against volcanic rock and xenoliths of the volcanic rock are seen in the diorite. Inclusions of andesite within the diorite were also noted in drill core from different zones of the deposit.

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[1]Quarry here refers to a relatively recent excavation site (1990s) where diorite was extracted and crushed for use as aggregate material. The quarry has no significance to the previous mining of the area, but it does provide excellent exposure of the diorite host rock.

The diorite is well exposed in a quarried wall in the Coxheath Zone (Fig. 1) and scattered outcrops towards the Deep Pit area, which form the basis for the following observations. The diorite is massive and its texture varies from seriate to hypidiomorphic granular with ≤5% amphibole and ≤30% plagioclase phenocrysts. A well developed set of conjugate fractures occurs (see below). Mineralogically the diorite is dominated by calcic plagioclase with normal zoning of An_{30-58}, amphibole of edenite-magnesiohornblende composition, and accessory apatite, titantite, and unmixed Fe-Ti oxides. At least two stages of magmatic amphibole crystallization occurred, based on textural relationships, and later overgrowths related to orthomagmatic to hydrothermal activity occur (DeWolfe, 2000). Rare examples of altered, remnant pyroxene occur in the diorite and some biotite, of olive-green color, is present in the diorite of the Deep Pit Zone. In addition, two unusual petrographic features are noted about the diorite throughout the area. (1) The first is the occurrence of small cavity-like areas (≤2-3 mm) that are filled with subhedral to euhedral quartz, albite and flame perthite (Fig. 2a). The albite in these areas may contain abundant disseminated needles of apatite. The origin of this feature remains unresolved, as it may represent a late magmatic or early orthomagmatic phenomenon. (2) The second feature is the presence of anhedral to suhedral quartz coring plagioclase grains without signs of hydrothermal alteration (Fig. 2b). Although there is an increase of these features in mineralized areas, it is not obvious if they are an alteration-related phenomenon. Commonly, the diorite has fine-grained disseminations of white mica within the plagioclase, and chloritic alteration of the amphibole and biotite.

The volcanic rocks vary from massive, aphanitic to variably porphyritic with ≤20% plagioclase phenocrysts of 2-7 cm length (Fig. 2c). The variable proportion of phenocrysts suggests multiple flow units, but these have not been distinguished in the field. In thin section, the volcanics are dominated by plagioclase laths, chlorite and disseminated opaques.

Petrology of Dyke Rocks in the Coxheath Area

Dyke rocks include both mafic and felsic types, and have been observed both in outcrop and drill core and within the diorite and volcanics. Several mafic dykes of <1 m width, steeply dipping and with northeast to easterly strikes, occur in the quarry area, but wider dykes (to 5 m) have been observed elsewhere in the area (Chatterjee and Oldale, 1980). The mafic dykes look like volcanic rocks when fine grained, have ≤5% plagioclase phenocrysts (≤3-5 cm length), and may have chilled margins (1-2 cm). In thin section the dykes have a trachytic texture, are dominated by plagioclase laths (60-70%) and chlorite (20-25%), with minor carbonate and Fe-Ti oxides, and its altered equivalent leucoxene. The aplitic dykes occur in the Deep Pit grid area, are flat lying, 2-10 cm thick, have a granitic mineralogy and a saccharoidal texture. The mafic and felsic dyke rocks have minor propylitic and carbonate alteration and no mineralization was observed within or cutting them. The timing of dyke emplacement is poorly constrained. Those with alteration similar to that related to the mineralization are presumed to be part of the Coxheath plutonic-volcanic suite, but where such alteration is not present the age is unconstrained.

Figure 2 (facing page). (a) Photomicrograph of diorite showing miarolitic-like cavity fill with anhedral alkali feldspar. Note the euhedral terminations of the plagioclase projecting toward the cavity, reflecting growth into a once open space. (b) Plagioclase with fine-grained white mica alteration and subhedral, graphic-like textural intergrowth of quartz. This feature occurs throughout the diorite, but is more prevalent near mineralized areas. (c) Outcrop photo of plagioclase phryic andesite. Note the conjugate fracture pattern (i.e. cooling joints) and pen knife for scale (8 cm). (d, e) Propylitic alteration focused along fractures in andesite (d) and diorite (e). Note the conjugate orientation of fractures in these units (also see Fig. 3b). Pen knife for scale is ca. 8 cm. (f) Slab of sulphide-bearing (i.e. chalcopyrite), quartz-cemented, monolithic volcanic breccia. Note the angular nature of the fragments and local jigsaw texture, and the fact that this is a matrix-supported breccia (i.e., must have been hydrostatically supported). (g) Outcrop of stockwork vein at west end of quarry face in Coxheath Zone. The margin of the vein sytem, as delineated by area of intense fracturing, alteration and veining, is indicated by the dashed lines. Note that the vein is discordant to the orientation of conjugate fractures, indicated by the dashed lines, in the diorite host to the left of the vein. (h) Outcrop photo of sheeted vein system in the Deep Pit area. Note the high density (i.e. 100-300/metre) of fracture-controlled veins, which contain sulphides.
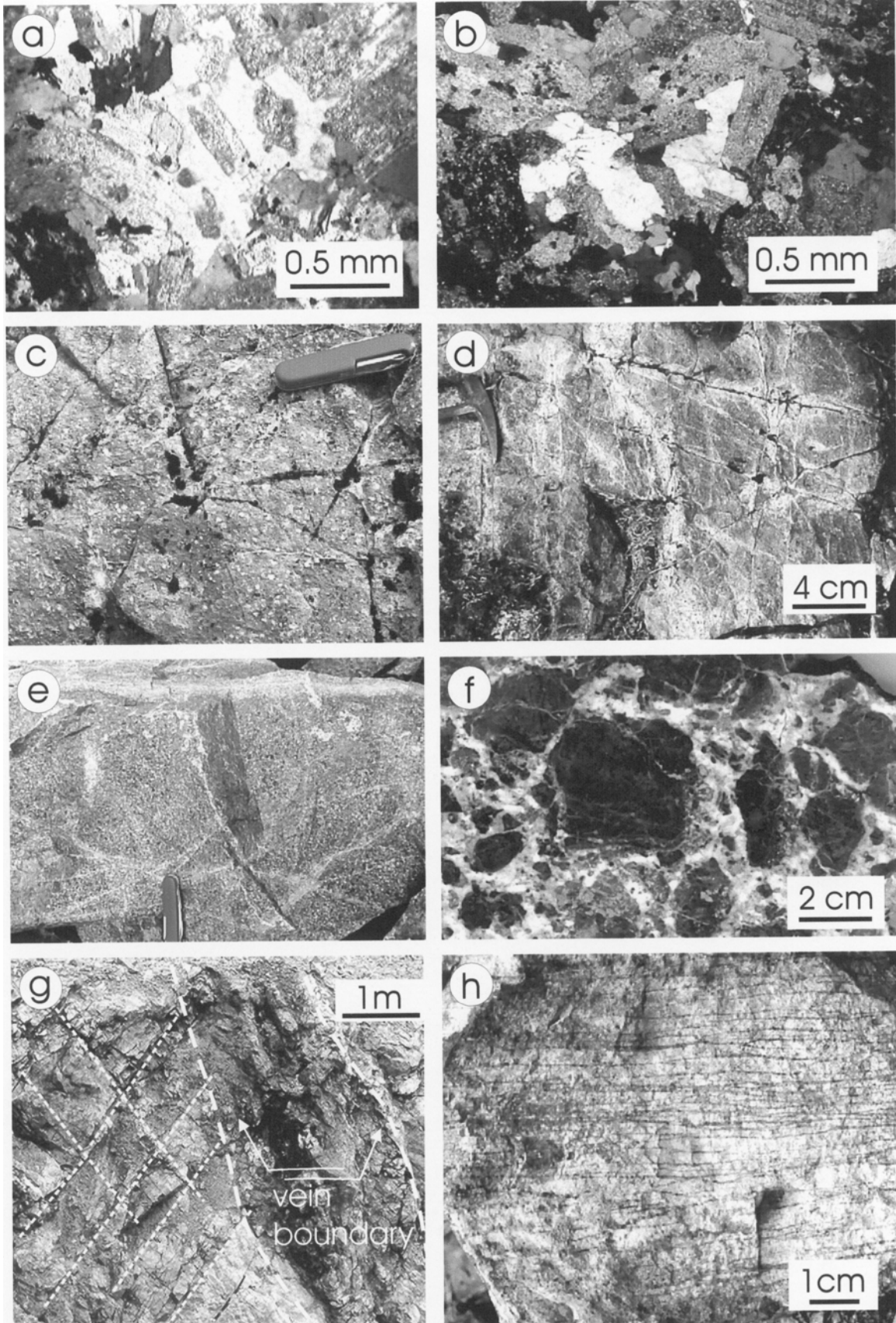
Structural Features in the Coxheath Deposit Area

Several structural features are present in the Coxheath area that presumably represent pre-, syn- and post-mineralization phases in the area. The earliest structures are conjugate joints or fractures observed in both the diorite and volcanic rocks (Fig. 2c, d, e). The joints are moderately to steeply dipping, strike northeast and northwest (Fig. 3a), and may form a locus for both propylitic and intense carbonate alteration (Figs. 2d, e, 3b). However, no mineralization has been observed along these fractures.

Vein structures consist of two types, referred to here as stockwork and sheeted veins. Stockwork veins occur as large vein swarms and include the past-producing vein systems of the Coxheath Zone, referred to previously as the four sub-parallel shear zones known as the B, C, D and LW veins. One of these is exposed at the west end of the quarry face in the Coxheath Zone (Fig. 2g) where it can be seen to have a different orientation than the conjugate fracture sets (compare structural data in Figs. 3a and 3c). These veins consist of brittle to ductile domains of 1-2 m width that have clearly defined boundaries. Within these zones the rock is strongly deformed with abundant fractures that focused fluids, resulting in mineralized vein formation. These veins are characterized by an abundance of tourmaline and feldspar alteration. The sheeted veins (Fig. 2h) occur extensively within the Deep Pit grid area where they have northeast strikes and steep dips (Fig. 3c), are closely spaced (i.e. 100-300 m) and subparallel, and are dominated by quartz, epidote and chalcopyrite. The diorite in this area is pervasively altered with potassic, propylitic and silica types occurring.

Hydrothermal breccias occur in various places within the deposit area (Fig. 2f) where mm- to cm-size, rounded to angular fragments of volcanic rock are cemented by fine-grained silica. The breccias sometimes contain abundant (5-20%) sulphides (pyrite, chalcopyrite) intergrown with the matrix quartz.

Several late structural features occur, including ductile shear zones and brittle faults which are best observed in the Coxheath Zone area. In one location, a steep fault forms the contact between the diorite and volcanics on the east side of the quarry. The structures vary in thickness and orientation (Fig. 3d) and have variable proportions of quartz and calcite. In some veins laminated carbonate occurs with fragments of wall rock diorite; these veins may form an en-echelon array. Other veins have coarse, oriented, dogtooth carbonate filling multi-cm wide openings. Rare barite occurs in some of these veins. In thin sections, late quartz-carbonate veins are commonly seen cross-cutting earlier alteration and mineralization.

Mineralization and Alteration

Mineralization in the Coxheath area is represented in the Coxheath, Mountain and Moly (also Central) zones and the Deep Pit area (Fig. 1). As a more complete description of these areas is in preparation, only a brief summary is given here and descriptions are also found in Lynch and Ortega (1997) and Chatterjee and Oldale (1980). The Coxheath and Mountain zones contain west- to southwest-trending shear zones (Fig. 2g) containing tourmaline-sulphide veins (i.e. stockwork veins above) of variable density and width, which are bordered by an alteration assemblage that replaces the host diorite. A typical example of this is shown in Figure 4a where a vein of massive tourmaline is connected to a stockwork system of tourmaline veins which cross-cut altered diorite, now a mass of potassic and sodic feldspar. Characteristic of the potassic feldspar of this zone is the enrichment of barium (≤ 4.5 wt. % BaO), as determined from electron microprobe analysis (DeWolfe, 2000). The tourmaline veinlets are mm to multi-cm wide and contain masses of fine-grained tourmaline or coarse acicular grains disseminated within the quartz-feldspar alteration halo (Fig. 4b). Some of the veins have a fibre texture and are cored by euhedral, acicular quartz and indicate extension prior to vein fill, whereas the finer-grained massive tourmaline reflects mostly replacement. Coring some of the areas between veins are areas of propylitic alteration containing carbonate, chlorite and epidote. Sulphides in this area include pyrite, chalcopyrite and bornite, which show a strong spatial association with tourmaline-rich areas.
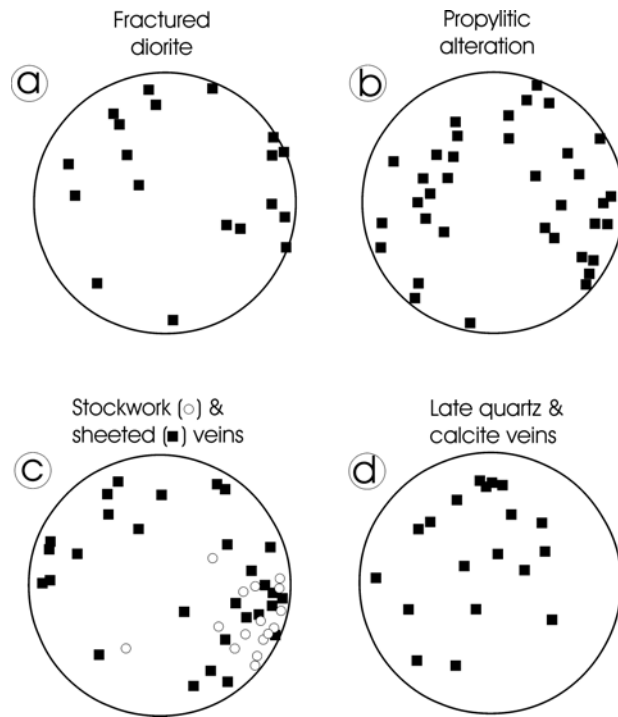
Figure 3. Stereographic plots of structural data for the Coxheath area. (a) Orientation of conjugate fractures in the diorite. (b) Orientation of propylitic alteration along fractures in the diorite and volcanic rocks. (c) Orientation of stockwork (see Fig. 4a) and sheeted veins (Fig. 4c). (d) Orientation of late quartz and carbonate veins.

A feature of the altered diorite is the presence of both Ti- and Na-rich amphibole overgrowths on early, magmatic amphibole, which occurs in close proximity to the Ba-rich feldspar (DeWolfe, 2000). The origin of these phases and how they relate to the mineralization is presently unresolved.

Mineralized breccia occurs in the Mountain Zone where altered, angular to variably corroded clasts of volcanic rock are cemented by a sulphide-bearing quartz matrix. The breccias are generally matrix supported and, therefore, must have been hydrostatically supported. This conclusion is also supported by the presence of primary, vapor-rich fluid inclusions in euhedral quartz (Fig. 4e). The clasts are intensely chloritized (to 99%) and secondary, fine-grained

white mica, fine-grained anhedral quartz, rutile and leucoxene also occur. The fragments are cut by micro-veinlets of quartz that emanate from the matrix material. This quartz is characteristically undeformed, subhedral to euhedral in shape (Fig. 4d), and may contain zonally arranged, vapor-rich fluid inclusions (Fig. 4e). Sulphide minerals include pyrite and chalcopyrite. Samples of altered volcanics cut by magnetite-chalcopyrite-silica-white mica veins also occur in this area.

In the Moly Zone and Deep Pit grid chalcopyrite and molybdenite occur both in multi-cm wide quartz veins and sheeted quartz-epidote-sulphide veins (Figs. 2h, 4f). Gold in these zones is associated with high copper grades, but visible gold has not been identified. The quartz veins have silica-potassic alteration haloes which have modified the original diorite to the texture and mineralogy of a monzogranite granitic rock. One such mineralized sample containing quartz-molybdenum veins was selected for Re-Os dating (e.g. Selby *et al.,* 2002) to obtain a direct age of the molybdenum mineralization. The sheeted veins occur as a high density (100-300 m) of subparallel veinlets which are filled with variable mixtures of quartz-epidote-magnetite-hematite-chalcopyrite-bornite and also minor white mica, titantite and rutile. The titanite forms part of the alteration halo about the vein, whereas magnetite and hematite, after the magnetite, can occur within the vein and halo area. Areas between the veins may have residual plagioclase with disseminated white mica and chlorite and, in addition, this is where the anhedral to subhedral quartz occurs intergrown with the plagioclase in a graphic-like texture (Fig. 2b). The denser the concentration of the veinlets, the more complete the alteration of the host diorite, such that up to several tens of metres of altered rock contains ca. 0.5 wt.% Cu based on diamond-drill intersections.

Alteration types in the area include potassic, sodic, tourmaline and propylitic alteration. Potassic and sodic alteration are developed peripheral to areas intensely veined, such as those places where tourmaline is best developed.
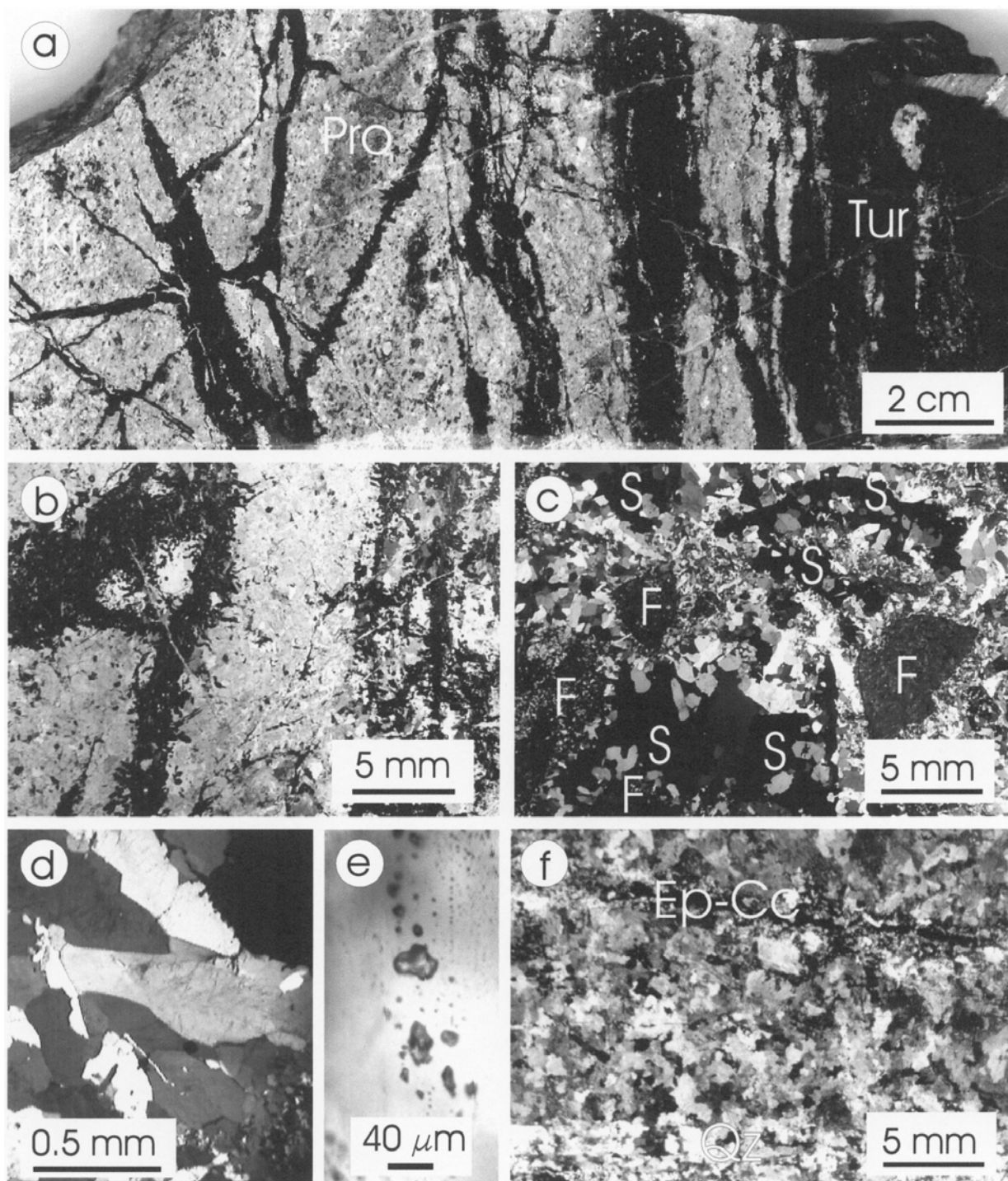
Figure 4. (a) Sample of tourmaline-rich alteration around stockwork vein system in diorite of the Coxheath Zone. Sample from west end of quarry face in Coxhearth Zone (see Fig. 2g). Abbreviations for alteration types are: Kf = Kfeldspar, Pro = propylitic, Tur = tourmaline. (b) Photomicrograph of sample in Figure 4a showing the tourmaline veinlets in altered diorite. Note the massive texture of the tourmaline with radiating tourmaline projecting from the massive tourmaline. Intervening material is altered diorite. (c) Silica-rich matrix to monolithic volcanic breccia from the Mountain Zone. Note the angular fragments (F) of altered andesite, pyrite and chalcopyrite (S), and euhedral quartz. (d) Photomicrograph of euhedral quartz grains in cement of breccia sample shown in Figure 4c. The quartz grains are growing around and outward from the fragments. (e) Plane of primary, vapor-rich fluid inclusions along growth zone in quartz of sample in Figure 4d. (f) Photomicrograph of sheeted-vein system (see Figure 2h) showing subparallel

Geological Features of Pyrophyllite-bearing Altered Volcanic Rocks

Approximately 4-6 km northeast of the Coxheath deposit area lies a sequence of felsic volcanic rocks, part of the Coxheath Plutonic-Volcanic Belt. These rocks contain zones of pyrophyllite developed within structural zones. Their occurrence, distribution, petrographic features and geochemistry are discussed in some detail in the following sections.

Occurrence and Distribution

Distribution of the altered volcanic rocks is shown in Figure 1 along with other known occurrences of pyrophyllite in the area. One of the areas located in Figure 1 was formerly quarried and mined by Dominion Steel Co. in the early 1900s. In the fall of 2002 trenching of this area was done by NSDNR in order to determine the extent of the pyrophyllite, assess its relationships to the surrounding rocks, and obtain samples for analysis. Trenching and location of additional outcrops in the area indicate the pyrophyllite zones: (1) are oriented in a northwest manner, (2) have both gradational and abrupt contacts with the surrounding felsic volcanics, and (3) define zones of ca. 15 m width and >150 m strike length. Their vertical dimension remains undefined, but the literature indicates that similar zones mined globally are vertically extensive and continue beyond the economic cutoff for the ore bodies. In outcrop the pyrophyllite-rich zones are not readily recognized as being significant despite the fact that they are composed predominantly of this valuable industrial mineral. However, once recognized the extent of the zone is easily determined because the outcrops are characterized by their light buff to pale pink colour and massive texture (Fig. 5a). The rock has a well developed, penetrative fabric and preferentially breaks along this direction. In addition, the pyrophyllite-rich zone in this particular area defines local topographic highs of northwest orientation.
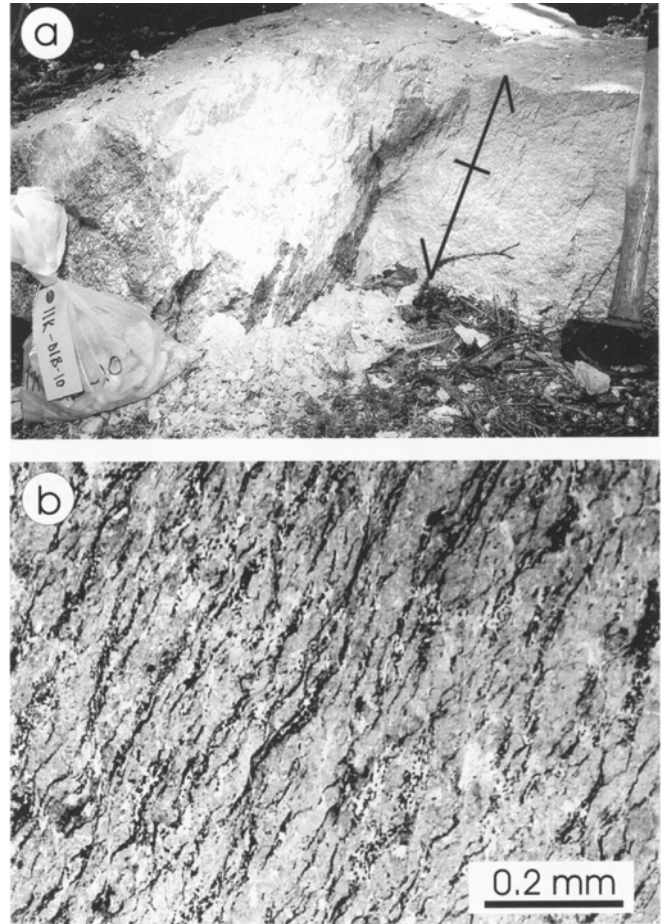
Figure 5. (a) Outcrop photo showing pyrophyllite-rich altered volcanic rock in northern part of the map area (see inset of Fig. 1). Orientation of the schistose fabric is indicated by the inclined cleavage symbol. Note hammer on right side for scale. (b) Photomicrograph of pyrophyllite-rich rock showing well-developed fabric. Dark lines defining fabric are altered oxides (i.e. rutile, leucoxene) and carbonate, whereas intervening areas are pyrophyllite and quartz.

We emphasize that previous workers had mapped out about 17 other zones of pyrophyllite in this area. Despite the general nature of the map containing these locations, the data nevertheless indicate that the zones are elongate and have variable orientations. The extent of these additional zones appears to be similar to that determined for the above mentioned zone, on the order of several hundred metres in strike length. Thus, collectively this indicates that there is significant tonnage potential for pyrophyllite.

Petrography and Mineralogy

The altered felsic volcanics are dominated by fine-grained phases that include clots of xenomorphic silica with subgrain development, abundant phyllosilicates, altered oxides (i.e. leucoxene, rutile), and carbonate. There is a well-developed planar fabric throughout (Fig. 5b) and uniform distribution of the mineral phases.

Given the very fine-grained nature and similarity of alteration minerals in volcanic rocks (i.e. various clay phases), detailed methods of mineral identification have been used to characterize the samples. In the first instance a sample of the altered volcanic rock was prepared as a polished section for examination with the electron microprobe using combined imaging and mineral analysis. Collectively, the imaging and analysis indicate the presence of quartz, pyrophyllite, diaspore and carbonate (Table 1). In addition, imaging analysis (Fig. 6) indicates the very fine-grained nature of the phases, generally several tens of microns, and their intimate intergrowth. The well-developed fabric seen in the hand sample was also seen during image analysis (e.g. Fig. 6b, c) where all the minerals were observed to be aligned parallel to this fabric, thus the minerals were either synchronous with or pre-dated fabric development.

In the second method of analysis, three samples of altered volcanics that had been crushed to <200 mesh for whole-rock chemical analysis, were analyzed using Philips Rietveld software at Queen's University, Kingston, Ontario. In this method, the X-ray lines recorded from the sample are used to determine the presence of minerals and their abundance can be quantified. The work is still in progress; however, initial results of the analysis of three samples are summarized in Table 2, where they are compared to the minerals present in high-sulphidization epithermal environments (White and Hedenquist, 1995). It is evident that there is a strong similarity between the mineralogy in the altered volcanics of Coxheath and the mineralogy expected in epithermal environments related to high-sulphidization systems.

Chemistry of the Altered Volcanic Rocks

Chemical analysis of sixteen altered volcanic rocks are presented in Table 3. Note that except for samples CB-05, 11KO1B 13 and 14, all of these samples come from the area in Figure 1 where the NSDNR trenching was done. Most of the samples are similar with respect to their degree of argillic alteration, but some differences are noted: (1) samples CB-02 and CB-05 contain some quartz veins, (2) 11K01B-13 contains a potassium-rich mineral phase, probably white mica based on the wt. % K_2O, and (3) 11K01B-14 contains albite and carbonate. The following points are noted regarding the major and minor element chemistry of these rocks (Table 3) and, for comparative purposes, they have been plotted with unaltered volcanic rocks of the Coxheath suite, grouped into basalts and andesites and rhyolites (after Barr *et al.,* 1996) in Figure 7. (1) These rocks have high silica levels typical of rhyolites, with the exception of two samples with >80 wt.% SiO_2 due to the presence of quartz veins. (2) Most samples show extreme enrichment in alumina with 18 to 25 wt. % Al_2O_3, which compares to 12-15 wt.% Al_2O_3 in the unaltered rhyolites. The exceptions to this are the two rocks that have quartz vein material that has diluted the alumina content and two samples that are not as pervasively altered. (3) The altered rocks are all extremely depleted in alkalies, with both potassium and sodium stripped in all but two samples. (4) The abundances of iron, magnesium and calcium are also very low. (5) The abundances of titanium and phosphorus are similar to unaltered felsic volcanic rocks in the area, thus these elements may be used as indicators of the primary chemistry of the altered rocks (see below).

In the Al_2O_3 versus SiO_2 plot, representative muscovite and pyrophyllite are plotted on the binary diagram along with a tie line joining quartz and pyrophyllite. The altered volcanic rocks plot along this line at mixtures of 70 to 90% by weight of pyrophyllite. Thus, the analyzed samples are clearly dominated by this mineral phase. The lack of potassium in these rocks indicates that secondary

Table 1. Representative compositions of minerals in altered volcanic rock, Cape Breton.

Sample	CB-2002	CB-2002	CB-2002	CB-2002	CB-2002	CB-2002	CB-2002
Mineral	pyrophyllite	pyrophyllite	pyrophyllite	pyrophyllite	diaspore	diaspore	diaspore
Point	1	3	4	7	2	17	22
SiO_2	65.02	67.00	67.50	67.55	0.12	0.57	1.10
Al_2O_3	30.71	28.39	28.27	27.89	83.95	82.63	81.95
FeO	-	0.12	0.20	0.09	-	0.09	0.06
MnO	0.05	0.07	0.13	-	-	0.25	0.05
CaO	0.25	0.09	-	0.13	0.07	-	0.02
Na_2O	0.12	0.07	0.01	0.11	-	0.00	0.01
Total	96.31	95.97	96.51	96.48	84.45	83.55	83.30

white mica is not present in these samples (see K_2O+Na_2O versus SiO_2 plot in Fig. 7).

In terms of the trace element data for the altered volcanic rocks (Fig. 7), the following points are highlighted and again they are compared to data for unaltered volcanic rocks from Barr *et al.* (1996). (1) In plots of silica and titanium versus zirconium, the altered samples appear to overlap in part the field for unaltered volcanics. This is also seen in the Ti/Zr versus Zr plot, although there appears to be a slight enrichment of some samples in Zr. The nature of this Zr enrichment will be examined in more detail below in relation to mass gains and losses associated with the alteration. (2) In terms of Zr-Y, the altered samples clearly define a separate field, except for the two samples with only partial loss of the alkalies, in which case the Y values are similar to those in fresh volcanics. This is also seen in the plot of Ti/Zr versus Y, which highlights the Y-depleted nature of the samples. Similarly, in the Zr-Nb plot the altered samples define a distinct field and the two least altered samples fall in the same area as the unaltered volcanics. This suggests that there may be a depletion of Nb similar to the behaviour of Y.

Given that Ti and Zr in the altered rocks appear to be similar to the levels in the fresh felsic volcanic rocks, the Ti/Zr ratio has been used as a proxy for the primary, unaltered signature of the pyrophllite-bearing rocks and a measure of the degree of fractionation since Zr is an incompatible

element in this suite. Thus, using the Ti/Zr ratio it is evident that there is a slight enrichment of Ga in the altered rocks, but extreme enrichment in Pb (to 294 ppm), Ba (to 3.3 wt. %), and Sr (to 2387 ppm). Although not identified yet, the analyses clearly indicate that barite should be present in these rocks. In binary plots of Ba, Sr and Pb it is evident that these elements show a strong positive correlation. These elemental enrichments are significant as they are common in high-sulphidization systems (e.g., White and Hedenquist, 1995) and provide evidence of a magmatic fluid component to these rocks.

An important aspect of the geochemistry of altered rocks is whether the elemental enrichment/ depletion is a result of volume or mass changes (Leitch and Lentz, 1994). For example, changes in the density of a sample due to uptake of volatiles (e.g. H_2O) can change the concentration of elements (i.e. decrease apparent abundance) without gain or loss of these elements. Using the graphical method of Grant (1987), the average fresh and altered felsic volcanic rocks are plotted in a binary plot and two scenarios are examined, one being conservation of Al and the other conservation of Si (Fig. 8). Before further discussion it is important to emphasize that the primary nature of the altered rocks was probably rhyolite given that their Ti/Zr ratios are identical to those for the unaltered rhyolites of Barr *et al.* (1996) and quite distinct from Ti/Zr ratios of the less evolved volcanics. The primary nature of the rocks having been established, it is noted that conservation of Al
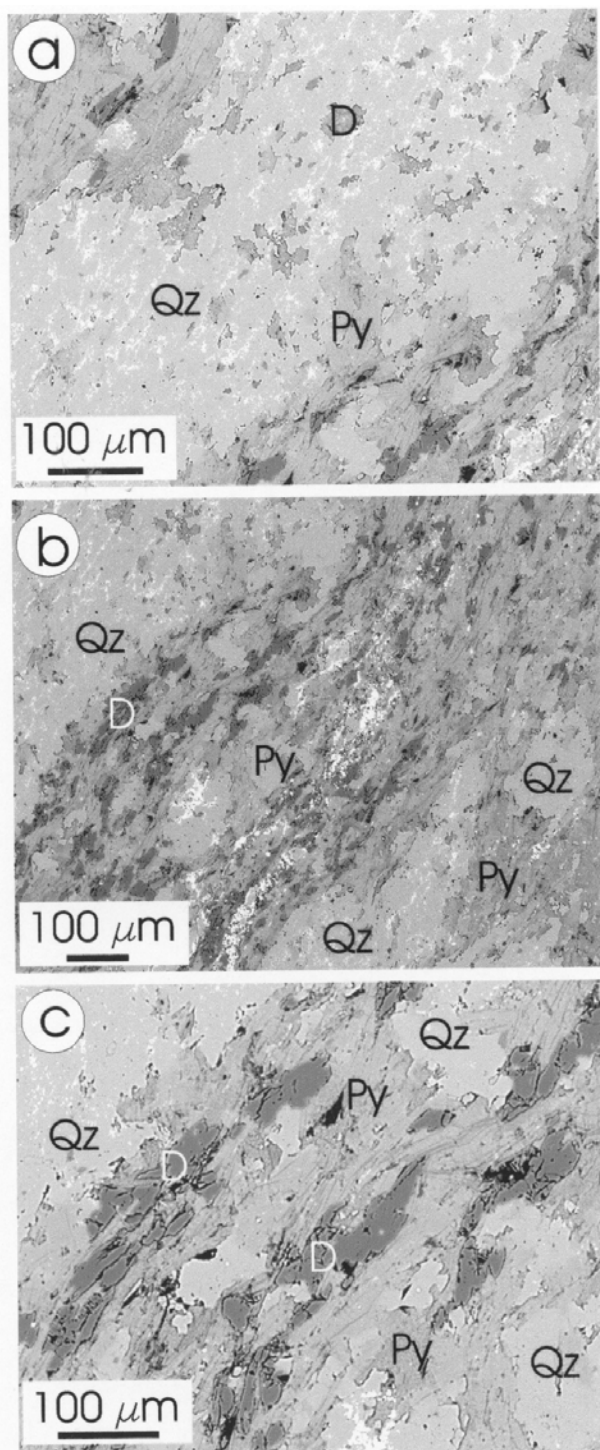
Figure 6. Back scattered electron images of sample in Figure 5b illustrating the mineralogy of the altered volcanic rock. In the images the mineral with the lower average atomic number is dark and the one with the highest average atomic number is brightest. Abbreviations are as follows: pyrophyllite (Py), diaspore (D) and quartz (Qz). The bright material defining a NE-fabric in 6b is rutile (i.e. Ti- rich), hence its brightness in the imaging.

indicates that Zr and Ga contents have also been conserved, but that there has been considerable loss of Si (i.e., 25%). Such loss of silica is considered unlikely given the already high levels for this element and that an upper limit of ca. 73 wt. % might be assumed given the nature of the precursor (rhyolite). In the alternative scenario, Si is assumed to have been conserved. In this case there is small enrichment of Al, Ga and Zr, which is what was suggested from the binary plots in Figure 7 (i.e. Zr and Ga versus Ti/Zr). This second scenario is considered more realistic for the following reasons. (1) The slight enrichment of Zr observed in these rocks is explained, whereas in scenario 1 a special suite of Zr-rich felsic volcanics is inferred, which is contradicted by the fact that the two least altered rocks have Zr values similar to the unaltered rocks. (2) The slight enrichment in Ga is accounted for in the altered rocks. (3) The depletion of Y of about 55% gives recalculated primary values of ca. 35-40 ppm that are consistent with Y in the unaltered rocks for similar Zr contents. (4) There is an increase in the aluminum contents of the rocks, as suggested by the absolute values of 18-25 wt. % Al_2O_3.

Discussion and Conclusions

The foregoing sections have presented the salient aspects of the geological setting, petrology, mineralogy and alteration, and nature of mineralization in two disparate systems, one a porphyry-type environment and the other an epithermal, high-sulphidization system. We suggest here that the relationship between the diorite-hosted, porphyry-style Cu-Mo-Au mineralization and the occurrence of extensive zones of argillically altered rocks (i.e. volcanics containing pyrophyllite, alunite, topaz, diaspore, and kaolinite) in the overlying coeval volcanics is more than coincidental. For example, we highlight the presence of celsian (i.e. Ba-rich) feldspar in the altered diorite, barite in late veins of the Coxheath area, and the anomalous content of up to 3% barium in the pyrophyllite rocks. Thus, we suggest the linking of these two disparate systems into a single deposit model based on the present knowledge of porphyry-epithermal systems. It has been suggested for some time that there is a continuum from the underlying coeval intrusive

Table 2. Summary of the mineralogy of samples from altered volcanic rocks, compared to the mineralogy of high-sulphidization systems (after White and Hedenquist, 1995).

Temperature (°C)					CB-05	CB-07	CB-011
100	150	200	250	300			
		epithermal ore					
silica					x	x	x
pyrite							
marcasite							
kaolinite					x	x	x
dickite							
pyrophyllite					x	x	x
illite							
diaspore						x	x
topaz							x
sulphur							
jarosite							
alunite						x	
rutile						x	

NB: rutile is not part of the alteration mineralogy

rocks to the petrogenetically related volcanic carapace (e.g. Sillitoe, 1973). More detailed studies of mineralized districts over the past few decades have made more clear the relationship between the magmatic-source fluids and extensively altered and mineralized zones in high-level epithermal environments (e.g. Hayba *et al.,* 1985; White and Hedenquist, 1995). The alteration zones in these environments are distinguished based on their mineralogy such that low- and high-sulphidization systems are recognized and are considered to reflect the contribution of magmatic sulphur, originating as SO_4, from a shallow magmatic system. The mineral assemblage identified in the pyrophyllite-rich zones is indicative of a high-sulphidization system and suggests, therefore, an underlying magmatic source for sulphur. This conclusion suggests that there may also be potential for base- and precious-metal mineralization, and the relative proximity of the Coxheath mineralized environment further supports this model.

An example of a mineralized district that might be used as a comparative model for the Coxheath area is found in the Maricunga belt of northern Chile. In this region, Vidal and Sillitoe (1991) integrate data from several porphyry-epithermal deposits into a single unified deposit model. The richly mineralized area of this part of the Andes is underlain by an igneous and sedimentary basement of Paleozoic and Mesozoic age, which is overlain by a richly mineralized Miocene andesitic-(dacitic) stratovolcano landscape which is cut, at depth, by composite porphyry stocks of diorite and quartz diorite composition. In the porphyry deposits, gold-copper mineralization is associated with K-silicate alteration, whereas in the higher-level volcanic rocks gold is found in zones containing pyrite- and alunite-rich advanced argillic alteration, with barite, native sulphur, enargite and vein-type mineralization. Minor inter- to late-mineralization hydrothermal breccias are commonly present. Examination of one of the deposits of this belt in

Table 3. Whole-rock geochemistry of altered volcanic rocks in the Late Proterozoic Coxheath Group, Cape Breton Island.

Sample	CB-01	CB-02	CB-05	CB-06	CB-07	CB-08	CB-09	CB-10	CB-11	11K01B 13	11K01B 14	11K01B 15	11K01B 16	11K01B 17	11K01B 18	11K01B 19
Major elements (wt. %):																
SiO_2	73.26	83.77	84.09	71.71	71.16	70.7	69.94	71.82	67.02	72.73	69.87	69.67	75.24	66.55	71.13	71.18
TiO_2	0.736	0.256	0.405	0.688	0.664	0.764	0.69	0.659	0.649	0.428	0.266	0.637	0.563	0.569	0.524	0.63
Al_2O_3	20.26	11.78	11.82	20.39	21.73	21.81	22.5	21.07	25.11	14.34	10.68	24.1	18.61	19.48	22.02	21.85
Fe_2O_3	0.2	0.26	0.26	0.14	0.35	0.53	0.31	0.21	0.15	1.68	1.6	0.11	0.18	0.18	0.17	0.18
MnO	0.001	0.003	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.007	0.103	0.073	<0.001	<0.001	0.001	<0.001	<0.001
MgO	0.02	<0.01	<0.01	0.01	0.01	0.01	0.02	0.01	0.02	2.06	0.21	0.02	0.02	0.02	0.01	0.01
CaO	0.12	0.11	0.05	0.55	0.08	0.06	0.07	0.06	0.15	0.44	5.4	0.09	0.11	0.05	0.06	0.07
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	4.06	<0.01	<0.01	0.03	<0.01	<0.01
K_2O	0.01	0.02	0.06	0.03	0.06	0.03	0.04	0.01	0.01	3.93	1.8	0.03	0.07	0.04	0.02	0.02
P_2O_5	0.162	0.072	0.061	0.19	0.295	0.213	0.232	0.126	0.177	0.058	0.059	0.217	0.255	0.187	0.156	0.162
L.O.I.	4.13	2.4	2.13	4.65	4.84	5.54	4.72	4.33	5.42	3.69	4.11	4.78	4.06	5.1	5.23	4.84
Totals	98.9	98.67	98.88	98.36	99.19	99.66	98.52	98.3	98.71	99.48	98.13	99.65	99.11	92.21	99.32	98.94
Trace elements (ppm):																
V	80	36	57	79	72	81	75	72	74	54	31	79	65	93	68	68
Cr	12	14	22	9	9	10	12	14	7	8	21	9	4	4	6	6
Co	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Zr	366	192	214	300	419	394	375	265	320	237	164	335	340	422	310	325
Ba	1448	1241	299	1521	519	70	545	<25	<25	314	433	166	278	33077	7304	1497
La	46	21	37	63	44	51	36	64	69	25	30	36	57	52	50	65
Nd	36	22	28	41	30	38	22	36	45	13	32	34	45	96	48	57
Ni	4	5	6	6	6	6	6	4	7	6	<3	4	6	<3	6	6
Cu	11	13	11	10	20	18	16	10	10	<5	6	12	12	12	13	10
Zn	20	20	22	20	19	19	19	19	18	250	35	17	19	21	19	18
Ga	19	17	14	19	19	18	19	18	21	17	7	21	23	20	22	20
Rb	<2	3	4	2	>2	<2	<2	2	<2	159	56	<2	<2	<2	<2	<2
Sr	763	419	368	859	2387	1634	1737	430	742	39	172	1139	1325	2238	1017	737
Y	19	14	15	19	22	17	16	17	13	41	35	10	16	11	11	15
Nb	8	6	6	8	8	8	8	7	8	10	9	6	7	9	8	8
Pb	49	38	25	48	87	75	84	39	57	41	19	68	72	294	168	99
Th	9	<2	19	17	5	8	8	17	24	8	4	10	12	10	21	19
U	<1	2	4	<1	<1	<1	<1	2	<1	5	5	<1	<1	<1	<1	<1

Analysis done at the regional XRF facility, St. Mary's University, Halifax

more detail is provided by Vila *et al.* (1991), who describe the nature of the Marte deposit of northern Chile which produced produced 66 tonnes of gold out of a porphyry gold system. The mineral deposit lies within a hornblende-biotite diorite stock that is part of a coeval andesitic stratovolcano. Gold distribution is related to a quartz vein stockwork surrounded by intermediate argillic alteration (chlorite-sericite-clay) with disseminated pyrite-Fe oxides. Minor chalcopyrite, molybdenite, tennantite, bornite and enargite occur, and remnant hydrothermal biotite and K-feldspar attest to earlier K-silicate alteration. Traces of tourmaline are noted. Intrusion breccia occurs, which is locally transected by hydrothermal breccias. An erosional remnant of the andesitic volcanic roof to the stock is largely replaced by a chalcedony- and alunite-rich advanced argillic assemblage, which is part of a larger tabular alteration zone.

As noted by Lynch and Ortega (1997), the features of the Coxheath Cu-Au-Mo system bear many similarities to the porphyry gold deposit type discussed by Sillitoe (1993). In addition, we have shown that the occurrence of altered volcanic rocks in the petrogenetically related volcanic carapace can be interpreted in the context of a high-sulphidization system. The present distribution of plutonic and volcanic rocks in this area suggest that this system has been tilted to expose the remnants of a porphyry-epithermal system of Precambrian age. Although additional work is clearly required to refine this model, it is felt that the geological features of the two systems have been documented sufficiently to support the model presented, and is testament to the occurrence and preservation of high-level hydrothermal systems back into the Late Proterozoic. Further evidence for this model and the potential for precious-metal mineralization is the occurrence of other high-sulphidization systems of Late Proterozoic age in the Avalon Zone of the Appalachians (e.g. Dubé *et al.,* 1998; O'Brien *et al.,* 1998).

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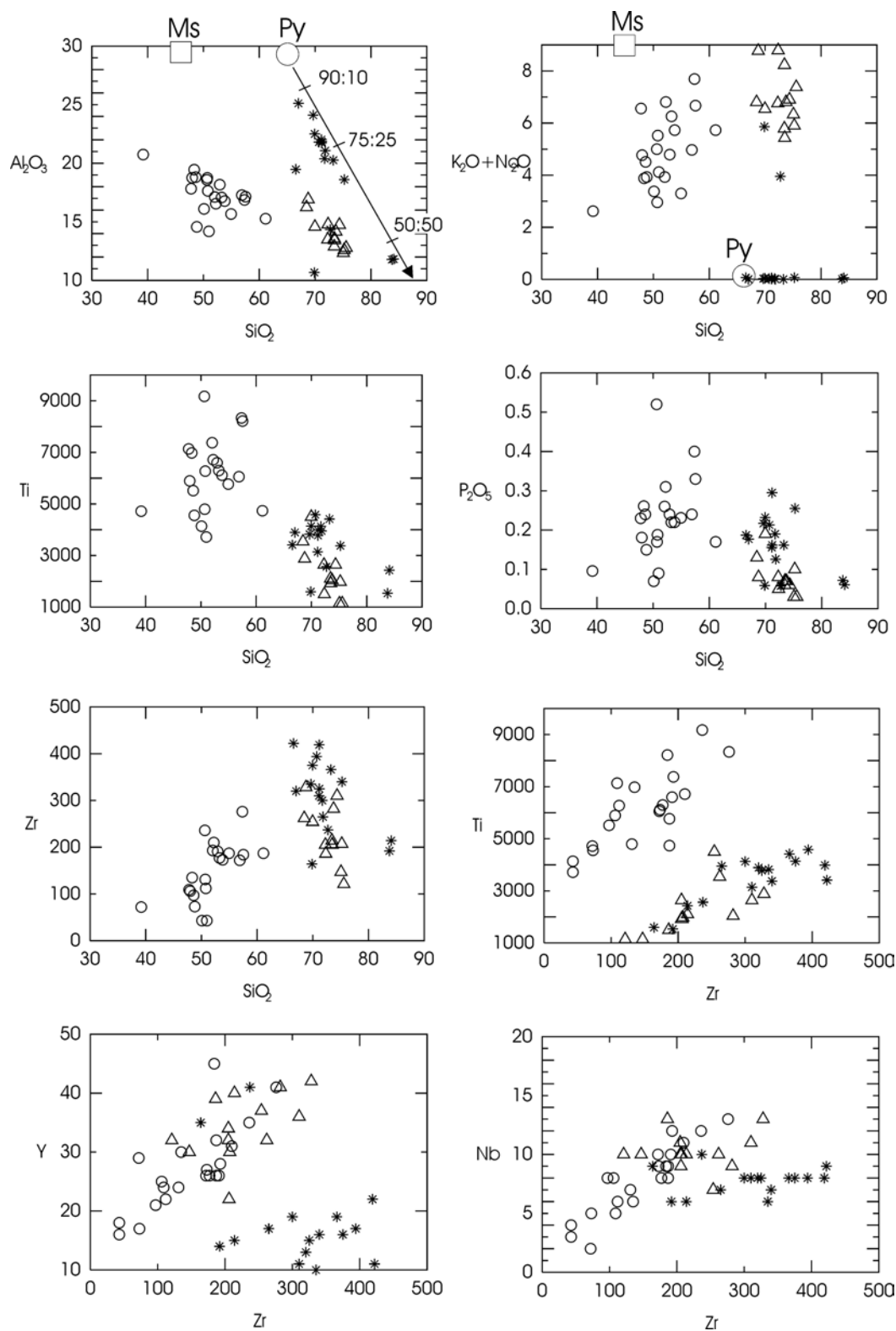
Figure 7. Binary element plots for suite of samples from the pyrophyllite-rich volcanic rocks (*) compared to the data base of Barr *et al.* (1996) for andesite (o) and rhyolite (▲).The abbreviations in the top plots are for muscovite (Ms) and pyrophyllite (Py). The tie line with numbers relates to the proportions of pyrophyllite and quartz mixtures, and indicate that the whole-rock samples in this study have mixtures of about 90:10 to 50:50 of these mineral phases. The arrow on the tie line points to 100% SiO_2 or quartz. Note that in the Pb versus Ti/Ar plot one sample is enriched in Pb (to 294 ppm).
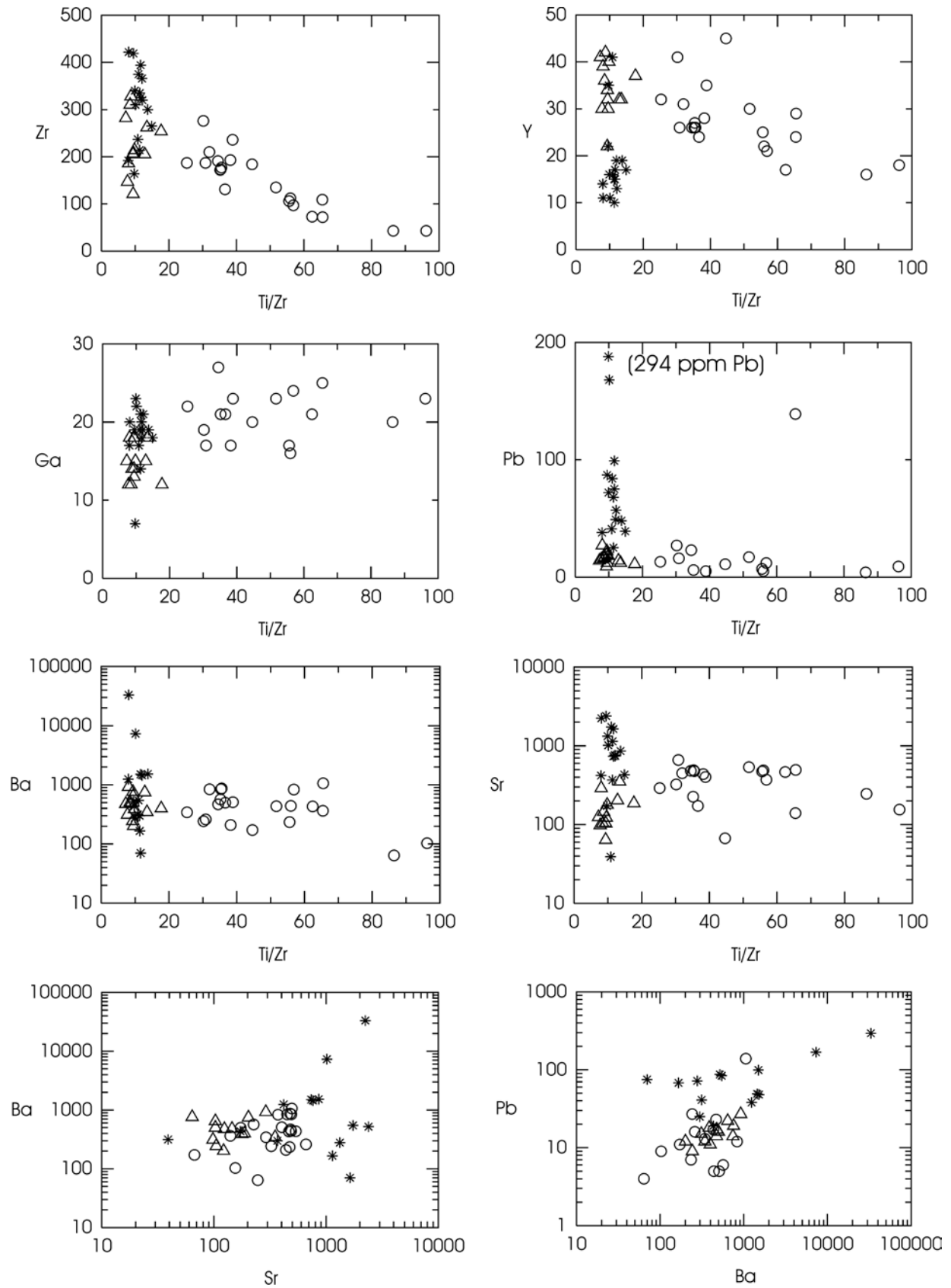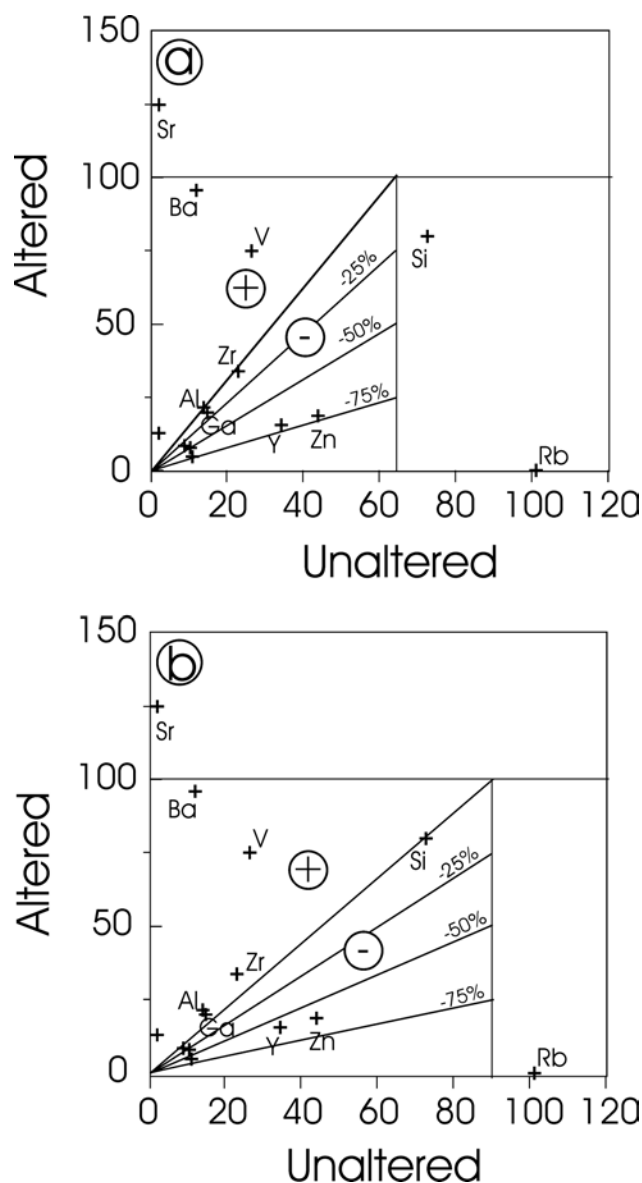
Figure 7. continued

Figure 8. Isocon plots (Grant, 1986) showing the relationship between the average rhyolite of Barr et al. (1996) and the average altered volcanic or pyrophyllite-rich rock of this study. The inclined line is an inferred constant mass line and the (+) and (-) signs refer to elemental gains and losses, respectively, for elements in the altered rock compared to the fresh rock. Two scenarios are represented here: (a) Al is inferred to have been conserved, (b) silica is inferred to have been conserved. The latter is the preferred interpretation, as discussed in the text.

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