Observations on Field Relationships, Petrology and Metallogeny of Southeast Cape Breton Island

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Introduction

This paper summarizes the results of field work conducted from June to September 1997 in southeastern Cape Breton Island between Little Harbour and Gabarus Bay (Fig. 1; NTS map areas 11F/10, 11F/09, 11F/15 and 11F/16), along with an integration of the work with previous studies in the area. The observations stem from the initial phase of a multi-year program to examine the pre-Carboniferous metallogeny of Cape Breton Island. The area was selected, in part, because it hosts the past-producing Stirling volcanogenic massive sulphide (VMS) deposit (Zn-Pb-Cu-Ag-Au) and many other promising environments for mineralization (e.g. Macdonald, 1989; Macdonald and Barr, 1993). In addition, the recently published report and accompanying map of Barr *et al.* (1996), representing the first synthesis of the area since Weeks (1954), provided an excellent base from which this work could progress. Field work consisted of an initial reconnaissance phase followed by more detailed studies in critical areas where important relationships could be observed. The emphasis of this initial phase of work was to gain an understanding of the regional geological setting of the area in order to determine what features were most important in controlling mineralization. It is well understood from studies of mineral deposits that all aspects of structure, host-rock petrology and alteration are important in terms of both exploration for and exploitation of mineral deposits, especially volcanic-hosted massive sulphide deposits (e.g. Franklin *et al.*, 1981; Nelson, 1997). It is also known that the geodynamic setting is important in terms of controlling formation of mineral deposits; therefore, part of this project will focus on documenting the broad-scale tectonic setting of southeastern Cape Breton Island through the Hadrynian and characterizing the associated magmatism.

Although not reported here, mineralization associated with Late Hadrynian (e.g. Coxheath) and Devonian (e.g. Gillis Mountain, Deep Cove, Blue Mountain) plutons was examined. Results of work at these localities will be reported at a later date.

Previous Work

The presence of the Stirling VMS deposit has attracted interest to the area for most of the 20th century, with development of the property in the 1930s and 1950s, and almost continuous exploration (summary in Patterson, 1993). The area was first mapped in detail by Weeks (1954), but it is the recent efforts of Barr *et al.* (1996) that resulted in recognition of the presence of several distinct rock suites that represent temporally distinct episodes of volcanic-plutonic activity. These authors also interpreted the geology of the area in the context of paleo-tectonic setting (Macdonald and Barr, 1993), concluding that the suites formed in continental margin volcanic arcs with later juxtapositioning along major faults. Barr *et al.* (1996) also present an excellent summary of the earlier field-oriented and lithogeochemical studies in the area, including several B. Sc. and M. Sc. theses.

The most thorough study of mineralizing environments in the area is summarized by Macdonald (1989) who conducted detailed work in a variety of settings, including disseminated sulphides in Hadrynian volcanic-sedimentary sequences and vein- and skarn-style mineral occurrences related to Devonian plutons. Barr *et al.* (1982) and Barr and Macdonald (1992) summarize the geology and petrology of plutons spatially associated with this latter style of mineralization. Deposit-scale studies at the Stirling deposit are limited and summarized in only a few publications. Watson (1954, 1957) expounded a structurally controlled replacement model, popular at the time, whereas Miller (1979) re-interpreted the geology in the context of the 1970s revolution in massive sulphide deposit studies and suggested an exhalative origin, as had Poole (1974) in an overview paper on massive sulphide deposits in the Appalachians.

Regional Geological Setting

The regional geology of the study area, simplified after Barr *et al.* (1996), is shown in Figure 1. Within the study

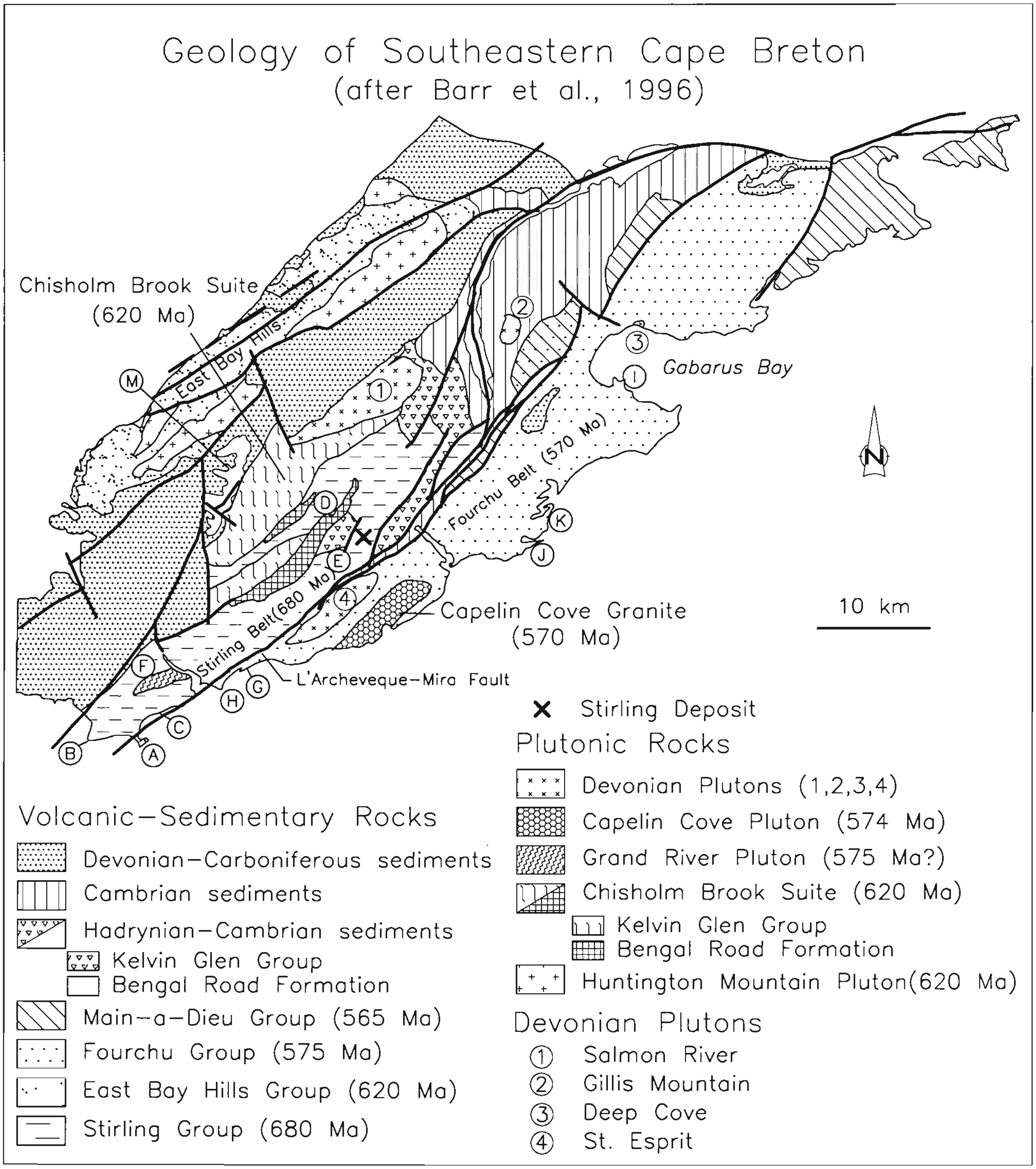

Figure 1. Geological map of southeastern Cape Breton Island (modified after Barr *et al.*, 1996). Points labelled with letters are localities discussed in the text. A = Point Michaud, B = Little Harbour, C = East Point Michaud Beach, D = Rory Neils Lake, E = L'Esprit Road, F = west of Grand River, G = L'Archeveque (Bottle Head), H = Black Point, I = Harbour Point, J = Cape Fourchu, K= Barren Point, L = Capelin Cove, M = Loch Lomond.

area several broad subdivisions can be made based on geological and geochronological constraints, and these are summarized in Figure 2. From east to west, the rock groupings include the 575 Ma Fourchu or Coastal belt, the 680 Ma Stirling belt, and the 620 Ma East Bay Hills belt. The Coxheath (620 Ma) and Sporting Mountain (620 Ma) belts are not included in this study. The Main-a-Dieu Group (≤565 Ma) is a lateral equivalent to the Fourchu Group. Plutonic rocks that intrude these belts of volcanic to sedimentary rocks are the Capelin Cove (574 Ma), St. Esprit (375 Ma), Salmon River (375 Ma), Chisholm Brook (620 Ma) and Huntington Mountain (620 Ma) plutons. The contact between the Fourchu and Stirling belts is represented by the northeast- to north-trending Mira-l'Archeveque Fault which, although not exposed, is inferred on the basis of different ages for the adjoining rock groups and nature of deformation (Barr *et al.*, 1996; author observations). Overlying the Hadrynian volcanic and sedimentary rocks are Late Hadrynian to Cambrian sedimentary rocks (e.g. Kelvin Glen Group and Bengal Road Formation); only the Kelvin Glen Group rocks were observed during the course of this study.

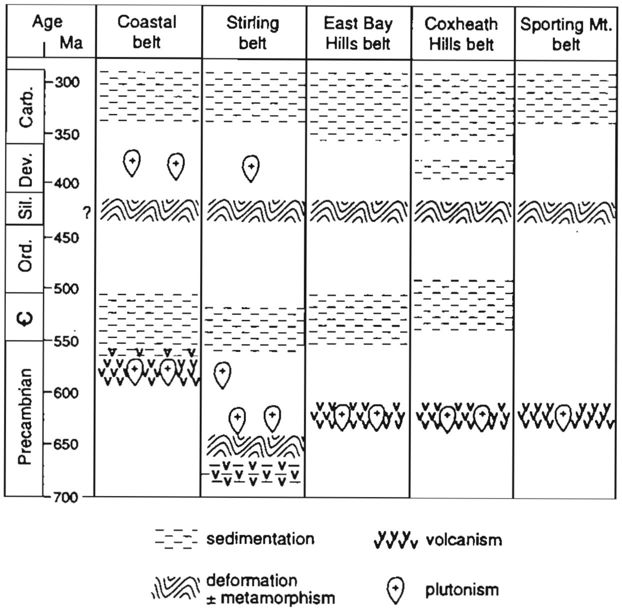

Figure 2. Summary of the geological evolution of Late Hadrynian belts in southeast Cape Breton (from Barr *et al.*, 1996).

Rocks of the area have been subjected to at least two periods of ductile deformation with the heterogeneous development, locally penetrative, of a northeast- to north-trending cleavage. Late development of brittle deformation is manifest by abundant kink zones. Folds are restricted to metre-scale structures and, although larger folds are suspected, they remain to be defined. Metamorphism is low grade with chlorite, epidote, albite and carbonate the common assemblage; P-T conditions are estimated at ca. 300°C and 2 kbars (S. Barr, personal communication, 1997), implying lower greenschist to sub-greenschist facies conditions.

Geological Observations

It is not the purpose of this paper to reiterate the geology of the area, as set out in Barr *et al.* (1996), but instead to add some new observations to the existing database. Thus, the following observations, based on recent field work, are intended to add additional information and hopefully some insight to our current understanding of the geology of the area. The discussion progresses from oldest to youngest rocks, and from volcanic-sedimentary to plutonic rocks, followed by a discussion of structural geology and types of alteration.

Volcanic-Sedimentary Rocks

Stirling Group (680 Ma)

Rocks of the Stirling Group are not well exposed due to the fact that they mostly outcrop away from the coast in low lying, heavily wooded, and in locally swampy areas. The exception is in the southwest, where exposure is excellent along the coast between Little Harbour and the mouth of Grand River. Exposures inland are best examined along recent road cuts and along streams. See Figure 1 for locations of the following areas.

Area 1 (Location C): East of Point Michaud coastal exposures of Stirling Group rocks reveal the presence of many features, as summarized in the schematic section in Figure 3. Several features (e.g. vesiculated tops, layering and grading in sediments) consistently indicate tops to the west, which means that the rocks at this locality represent the base of the Stirling Group sequence. Farther east of this locality the Mira-L'Archeveque Fault marks the transition to rocks of the Fourchu Group. The stratigraphy is dominated by flows of mixed basalt and basaltic andesite composition at the base which are cut by numerous feeder dykes that are discordant to semi-conformable with respect to the flows. Minor faulting of syn-volcanic origin locally controls the flows and injection of dyke rocks. The massive and vesiculated (i.e. amygdaloidal) flows are mixed with breccia horizons, interflow sediments and felsic tuffs. In some areas rafts of layered tuffs or sediments remain undisturbed where enveloped by basaltic dyke rock material. At the top of the section, felsic breccias and flows are intermixed with layers of texturally heterogeneous volcanics with mixed

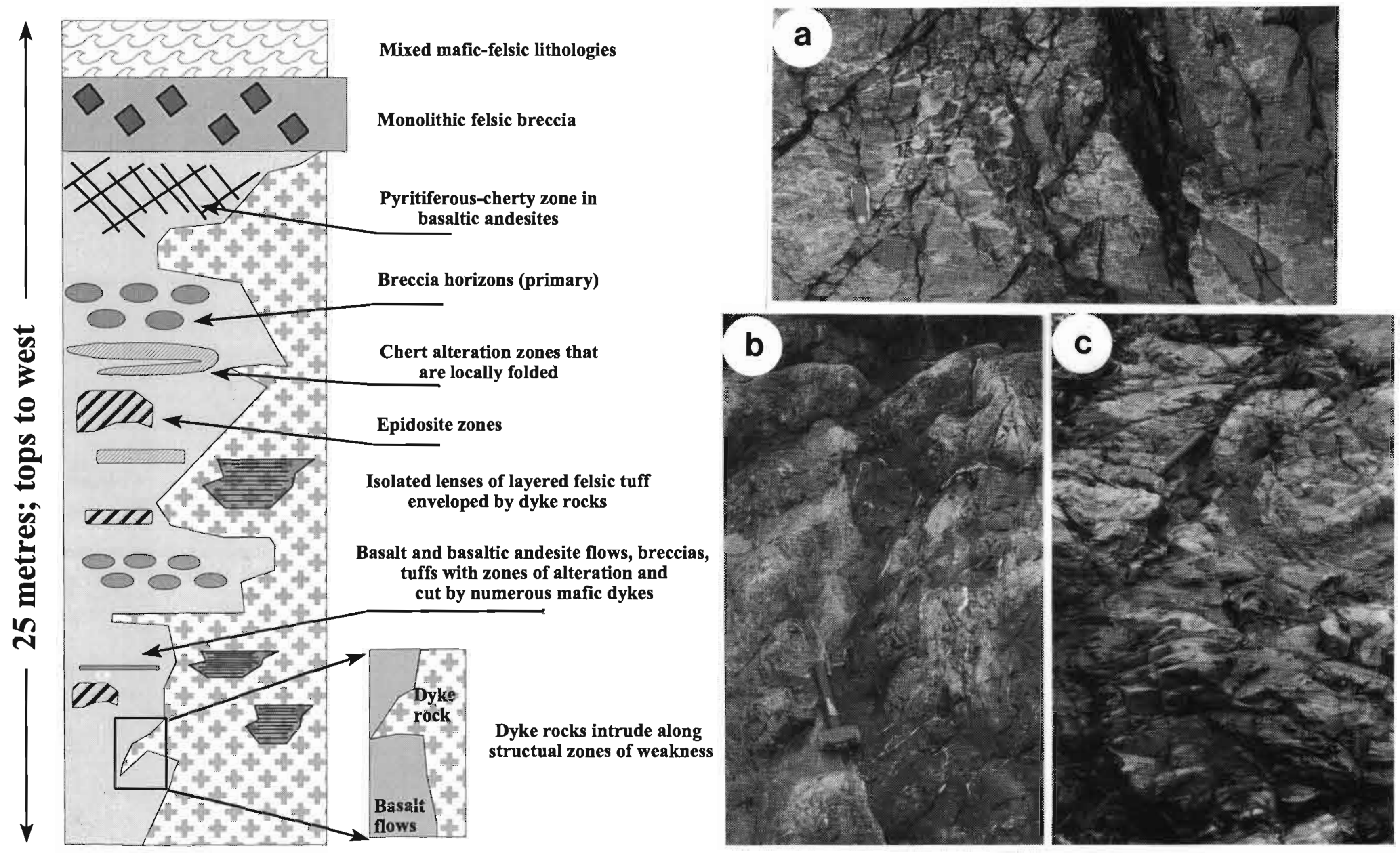

Figure 3. Schematic section summarizing observed field relationships in Stirling Group rocks exposed on East Point Michaud beach (locality C in Fig. 1). Inset photos illustrate the following. (a) Flow-top breccia (tops point downward) with cherty matrix (pen knife for scale) indicating younging to the west. (b) Dyke rock (to right of hammer) intruding basalt along an original bedding plane. Note the small offsets (normal faults) at the base of the sill (?). (c) Felsic tuff with primary layering enveloped by mafic dykes. Note that the orientation of layering in the tuffs is retained between the isolated lenses.

mafic-felsic components, thus indicating contemporaneous eruption of markedly different magmas. Alteration, both concordant and discordant, includes chert, pyrite and epidote, all of which are all developed at different scales and intensities. In addition, calcite and quartz occur in en echelon vein arrays, along cleavage and in joints or kinks.

Area 2 (Location D): An exceptional exposure of felsic breccia (unit Hsbr of Barr *et al.*,1996) is seen along a new logging road ca. 4 km east of Rory Neils Lake (Fig. 4). This unit consists of felsic breccia intermixed with lesser feldspar crystal tuff, crystal-lithic tuff and massive felsic rocks (flows ?), and has been interpreted by Barr *et al.* (1996) as being of autoclastic origin. A traverse through this unit exposes the following rocks: (1) a breccia rock consisting of variable size (to 1 m) fragments (massive to crystal-rich) in a matrix of similar bulk composition (dacitic to rhyodacitic; Barr *et al.*, 1996). In some instances fragments of earlier breccias are observed; (2) well layered crystal-rich and aphyric tuffs; and (3) massive, fine-grained mafic rocks, probably representing a single intrusion (i.e. single body as indicated on the map). Given that bedding in the rocks is highly variable and that rapid lithological variation is the norm, a local source or nearby vent is suggested. Within the volcanic sequence, there is locally an abundance of quartz veins and chlorite may also be abundant, occurring as a secondary mineral preferentially located along primary layering. The felsic breccia at this locality differs considerably from that seen immediately east of Rory Neils Lake where the rocks are more siliceous, dark purple in colour, relatively poor in crystals, and not so distinctly layered.

Area 3 (Location E): Rhyolite porphyry (unit Hsr of Barr *et al.*, 1996) is exposed along the L'Esprit Road some 1.2 km in from the main highway; this unit (unit Hsr of Barr *et al.*, 1996) is important since it is on strike with a very similar unit in the Stirling deposit area. The unit consists of at least 100 m thickness of massive, quartz-feldspar phyric rhyolite, dark green to black in colour, and locally veined by quartz, calcite and chlorite. Crystals ($\leq$5-7 mm) constitute 5% to 50% of the rock and are subhedral to euhedral. Petrographic examination of this unit indicates the following features: (1) quartz is badly embayed, fragmented and desegregated, but no obvious tectonic foliation is apparent; (2) feldspar phenocrysts, now albitic plagioelase (An_{3-10}), are variably altered to sericite, epidote and carbonate; (3) the matrix varies from a fine-grained mass of carbonate-epidote-actinolite-albite-biotite to a trachytic-textured mass of feldpsar microlites; and (4) areas of radiating actinolite occur. Combined imaging and electron microprobe analysis of this rock indicates that: (1) the matrix is dominated by an intergrowth of quartz-albite (An_{0-5}) (Fig. 5a, 5c) with very little potassium component (Fig. 5b); (2) two distinct plagioclase compositions are represented (Fig. 5c). Whereas the albite occurs intergrown with quartz, plagioclase of An_{30-50} composition occurs with micas enveloping the quartz-albite lenses and is anhedral. This calcic plagioclase is clearly not of magmatic origin, but perhaps early subsolidus origin; and (3) the biotite and chlorite appear to be in chemical equilibrium (Fig. 5d). Thus, whereas this sample appears fresh in the field it has clearly undergone considerable post-crystallization chemical exchange and textural modification.

A ca. 1-2 m thick zone occurring within this rhyolite porphyry unit consists of 20-50% pale coloured, elongate, porous material in a fine-grained, aphyric, dark green to black matrix; locally this rock is strongly schistose. The origin of this rock is unknown, but it could represent a primary fragmental unit with superimposed ductile deformation.

Area 4 (Location F): Exposure of fine- to medium-grained, dark grey to black clastic sediments (unit Hsla of Barr *et al.,* 1996) in recent quarries and road cuts west of Grand River allows a section of several 100 m thickness to be observed roughly perpendicular to the northeast strike of the unit. This section exposes a southward-facing sequence, as indicated by sedimentary structures, of dark grey to black siltstone and shale containing thin beds of coarser arkosic sandstone. The sedimentary package is overlain by a grey, monolithic breccia unit of several metres thickness containing angular, elongate fragments of possibly volcanic origin which indicates a marked change from the pre-existing depositional conditions within the basin. A composite section of this unit will be presented in a later report.

Fourchu Group (575 Ma)

The Fourchu Group is exposed almost continuously along coastal sections and thus it is possible to examine these rocks in detail. As noted by Barr *et al.* (1996), the package faces eastward and no new field data were found to contradict this observation.

Area 5 (Location G): The basal part of the Fourchu Group is well exposed on Little Head at L'Archeveque Cove and the on-strike continuation of the same rocks to the west at Black Point (Location H); both areas are easily accessible and exposures are exceptional. A partially schematic section based on the first locality (Fig. 6) illustrates some of the following important features: (1) top indicators, such as bedding and flow tops, are

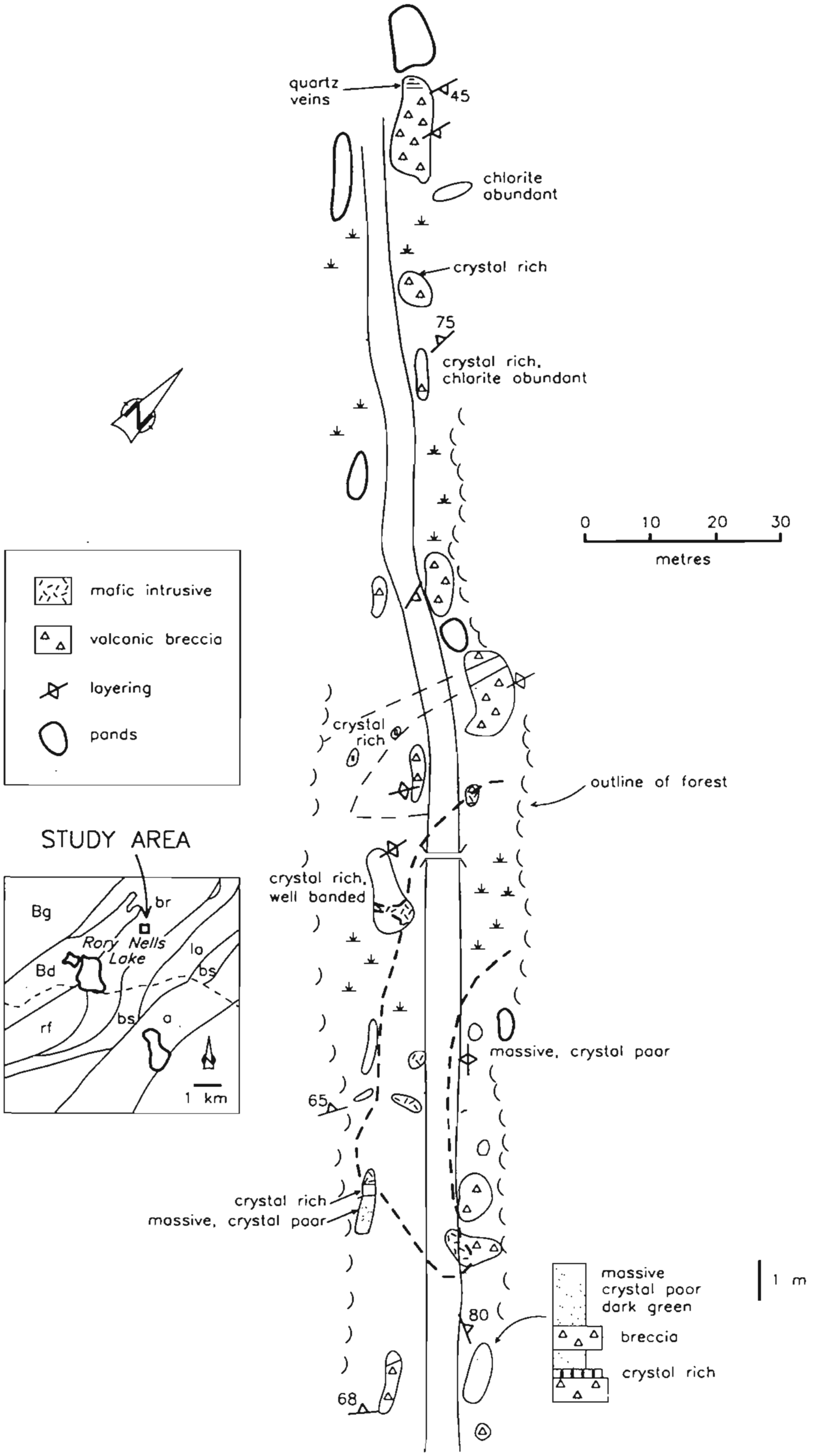

Figure 4. Map of the logging road northeast of Rory Neils Lake showing outcrop distribution and rock types within a felsic breccia sequence (unit Hsbr of Barr *et al.*, 1996). Unless noted otherwise, all rocks are pyroclastic. Units in the inset figure after Barr *et al.*, 1996: Bg - Chisholm Brook granodiorite; Bd - Chisholm Brook diorite; br - basalt, andesite, dacite breccia; la - litharenite; bs - basalt-andesite flow; rf - rhyolite flow and lapilli tuff; a - andesite lapilli tuff.

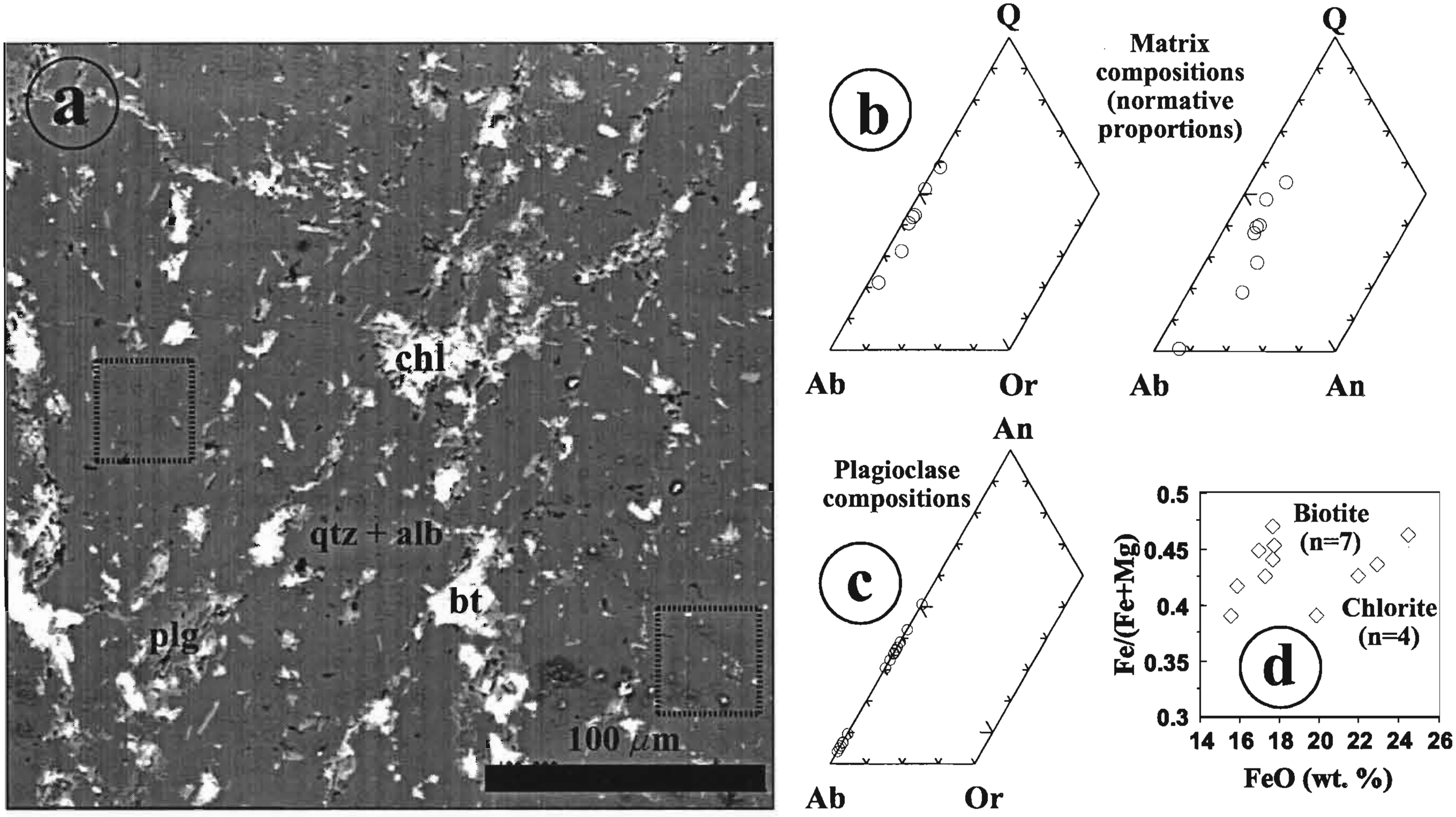

Figure 5. Petrography and chemistry for sample STB-97-104 from a rhyolite porphyry (unit Hsr of Barr *et al.*, 1996) collected from southwest of Stirling (Fig. 1). (a) BSE (back scatter electon) image illustrating in detail that the matrix consists of lens-shaped domains of quartz-feldspar enveloped by calcic plagioclase (An_{30-50}), biotite and chlorite. Minor amounts of muscovite, apatite, zircon, calcite and epidote are also present. (b) Quartz (Q) - albite (Ab) - orthoclase (Or) and Q-Ab-plagioclase (An) ternary plots showing normative proportions of minerals for the matrix domains analyzed by rastering areas with a 10 µm electron beam (see typical areas in Fig. 5a). Note that there is trace K and and only minor Ca in these areas. (c) Ternary plot for the two types of feldspar in the sample, plagioclase in the quartz-albite domains, and plagioclase that surrounds these areas (Fig. 5a). Note that there is a marked difference in composition for the two types of plagioclase. (d) Binary plot of Fe/(Fe+Mg) versus wt. % FeO for biotite and chlorite in the sample.

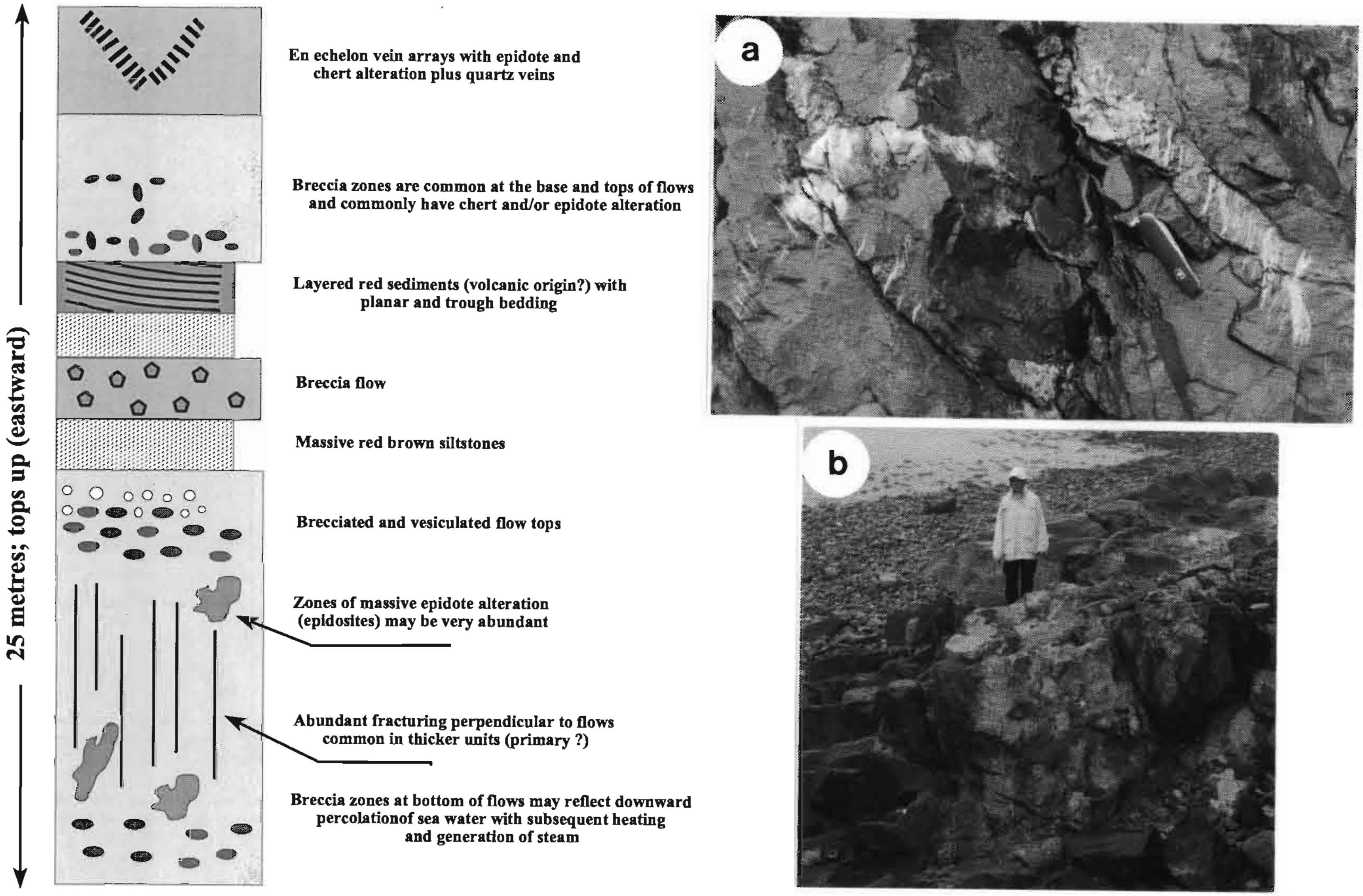

Figure 6. Schematic section summarizing observed field relationships in Fourchu Group rocks as exposed on coast at L'Archeveque (Bottle Head). Inset photos illustrate the following. (a) En echelon vein array with tension gashes infilled with epidote. (b) Extreme development of epidote-chert alteration at the base of a basalt flow.

abundant and consistently point eastward; (2) multiple flows are easily distinguished and these are commonly marked by flow top breccias, oxidized tops and interflow sediments; and (3) intense alteration, including chert and epidote, is common, with some carbonate and quartz veins also present. The epidote may occur as massive replacement material along bedding-concordant or -discordant zones and also as en echelon vein arrays (Fig. 6).

Area 6 (Location I): Along the south coast of Gabarus Bay there is excellent exposure of grey-green, dacitic to andesitic, crystal-rich lithic lapilli tuff with basaltic lenses (unit Hfg of Barr *et al.,* 1996). A section of this unit exposed at Harbour Point was examined in detail in order to ascertain the proportion of rock types; results of more detailed work on the measured section will be reported later. A map of the area by Macdonald (1989) indicates the presence of abundant felsite sheets which may have been feeders for volcanic rocks.

Petrographic examination combined with electron microprobe and image analysis of a felsic rock (Fig. 7) from this locality indicate the following: (1) the sample consists of phenocrystic feldspar, now albite, and quartz in a fine-grained matrix consisting of quartz-albite ($An_{0\text{-}5}$) domains separated by layers of epidote-orthoclase ($Or_{90\text{-}96}$) (Fig. 7a, b, d); (2) the domains of quartz and albite are very consistent in terms of bulk analysis (see QAP proportions Fig. 7c); and (3) potassium has been partitioned into the K-feldspar grains (Fig. 7b, c, d). Clearly this rock has undergone substantial post-crystallization chemical exchange and the composition of K-feldspar suggests that it occurred at ca. 350-400°C (Smith, 1974), thus well above the conditions of regional metamorphism, which may indicate that the assemblage of epidote - K-feldspar is part of an early, syn-volcanic, metasomatic event.

Plutonic Rocks

Chisholm Brook Suite

The Chisholm Brook suite was examined along the east side of Loch Lomond, along a road running along Kates Brook in the central part of the intrusion, and from the numerous logging roads within the northern and southern lobes of the intrusion. The site is described by McMullin (1984) and Barr *et al.* (1996) as consisting of dioritic rocks, quartz monzodiorite and granodiorite with abundant felsite dykes. Observations in this study indicate that considerable parts of the area underlain by granodiorite include red, medium- to coarse-grained monzodiorite. Mafic dykes commonly cross-cut the granodiorite and monzogranite phases. Textures indicative of magma mingling and mixing are common at the contacts of the mafic and felsic phases and are up to several 10s of metres wide. Magma mixing textures are best observed within a rock quarry in the eastern part of the intrusion (location in Fig. 1) where angular blocks (to 1 m^2) of dark fine-grained diorite occur in red monzodiorite (Fig. 8a) and acicular hornblende is abundant in areas of magma mixing (Fig. 8b). Petrographically the granites are dominated by quartz, altered feldspars, and chloritized biotite and amphibole with accessory phases of apatite, epidote and zircon; quartz is often paragenetically late and forms a granophyric texture with feldspars.

McMullin (1984) and Barr *et al.* (1984) present a large chemical database for the Chisholm Brook suite. The rocks range from 60 to 75 wt. % SiO_2, are calc-alkaline in character, and show continuous trends in Harker-type variation plots. Thus, the chemical features suggest a continuum between the mafic and felsic members of the Chisholm Brook suite, which may be interpreted to indicate that mixing of the different magmas was an efficient process. This aspect of the suite will be examined in more detail with further work.

Capelin Cove Granite

The Capelin Cove granite is well exposed along the coast between Capelin Cove and Kelpy Cove where it consists of: (1) a medium- to coarse-grained, white biotite granodiorite phase; (2) a medium- to coarse-grained, red monzogranite phase; and (3) porphyry dykes of feldspar to quartz-feldspar phyric types; similar dyke rocks are seen as boulders at the Stirling deposit and have been described from the underground workings. The southeast side of the granite is variably deformed by a ca. 0.5 km wide, northeast-trending, brittle to ductile shear zone. Just east of the contact, felsic dykes from the Capelin Cove granite cut Fourchu Group volcanics. The most characteristic feature of the Capelin Cove granite, as seen between West Head and Kelpy Cove, is the presence of angular to rounded mafic enclaves which are enveloped by ca. 1-3 cm wide, feldspar-rich reaction rims if hosted by the red granite phase (Fig. 8c). Reaction rims are rarely present within the more mafic granodiorite phase. As with the Chisholm Brook suite, magma mixing is considered to have been an important petrological process for the Capelin Cove granite. The red phase is also cut by quartz - red feldspar - hematite - green tourmaline veinlets (Fig. 8d) along its southern margin.

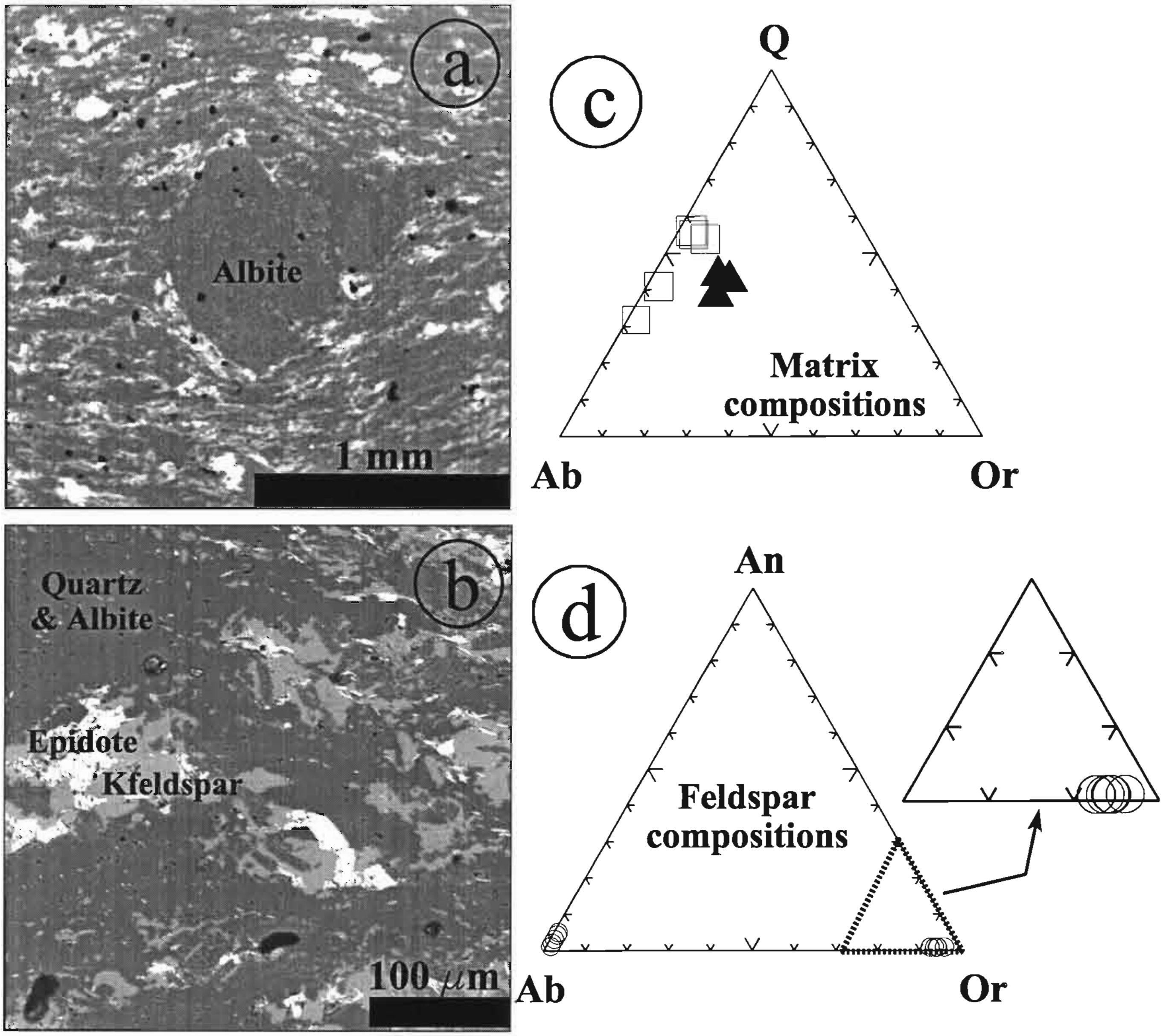

Figure 7. Petrography and chemistry for sample STB-97-177 from felsic porphyry (unit Hfg of Barr *et al.*, 1996) collected from Harbour Point, Gabarus Bay (location I, Fig. 1). (a, b) BSE (back scatter electon) images illustrating that the rock consists of plagioclase feldspar (now albite) phenocrysts in a fine-grained, flow-textured matrix of quartz-albite domains separated by thin lens of epidote-K-feldspar. (c) Quartz (Q) - albite (Ab) - orthoclase (Or) ternary plot showing normative proportions of minerals for the matrix domains analyzed by rastering areas with a 10 μm electron beam. K-free areas represent the quartz-albite lenses, whereas K-bearing areas are for analyzed domains that included the epidote-K-feldspar material. (d) Ternary plot for different feldspars in the sample, namely the albitic phenocrysts and the matrix K-feldspar. The enlarged part of the ternary plot for the K-feldpsar shows that the composition is Or$_{92\text{-}97}$.

Alteration

Alteration in the study area is best developed within, although not exclusive to, volcanic rocks and is most obvious in rocks of relatively mafic composition; observations with respect to alteration types are summarized in Table 1 and photos are shown in Figure 9. Preliminary examination of petrographic thin sections reveals alteration is even more pervasive than originally thought from field work, especially with respect to epidote abundance, thus the following comments are made with a certain degree of caution pending further work. Alteration

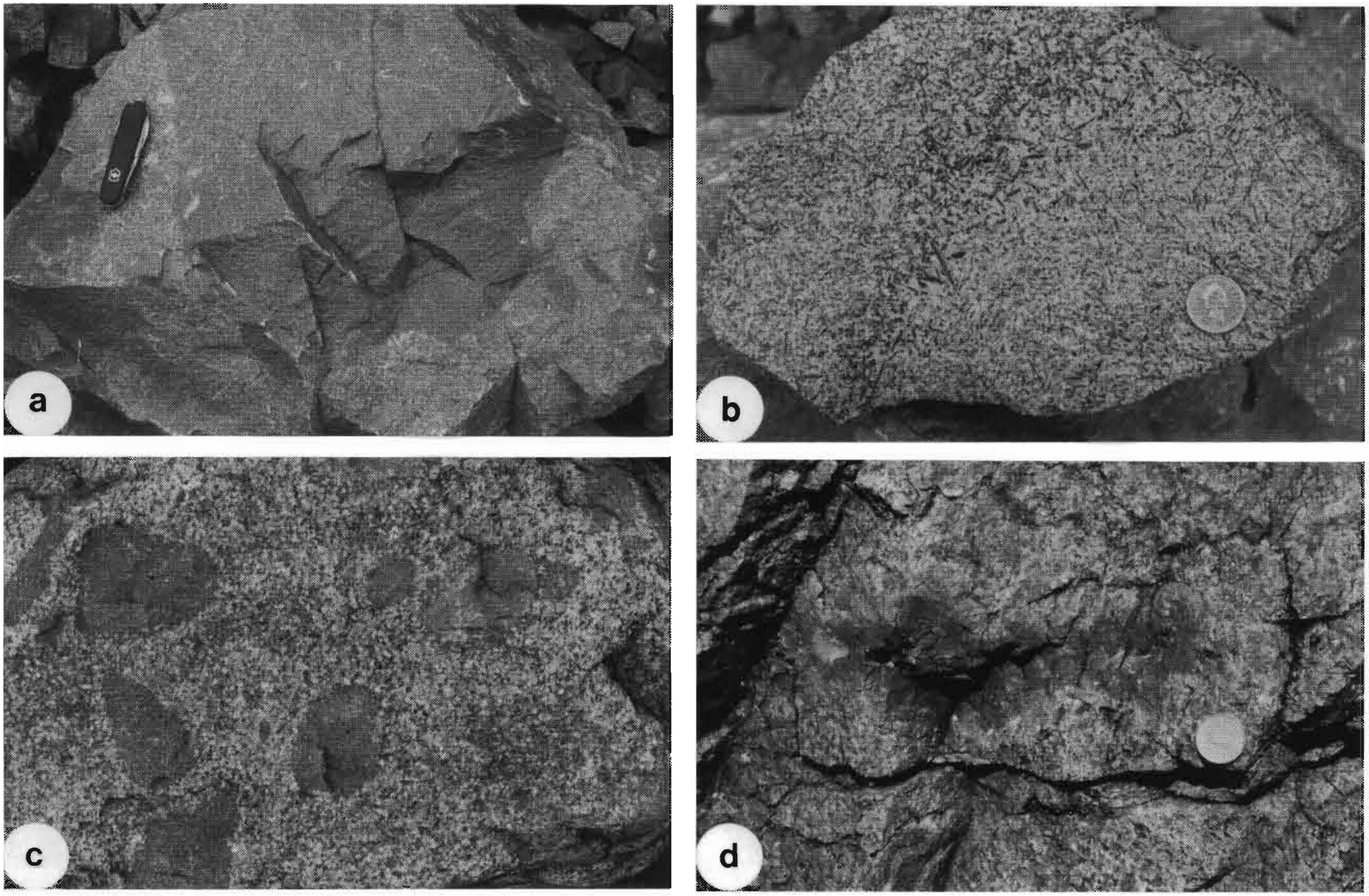

Figure 8. Photographs of the Chisholm Brook (a, b) and Capelin Cove (c, d), plutonic suites in the study area. (a) Dark, fine-grained mafic (i.e. dioritic) enclave in medium-grained, red monzonite or monzodiorite. (b) Acicular hornblende marking the contact between two texturally and chemically distinct phases of monzodiorite/monzonite. Note penny for scale. (c) Dark, fine-grained, plagioclase-phyric, dioritic enclaves with narrow quartz-plagioclase rim in matrix of medium-grained, red biotite monzogranite. Width of the enclaves is ca. 15 cm. (d) K-feldspar-tourmaline-quartz-hematite vug infill within red monzogranite. Note ten cent coin for scale.

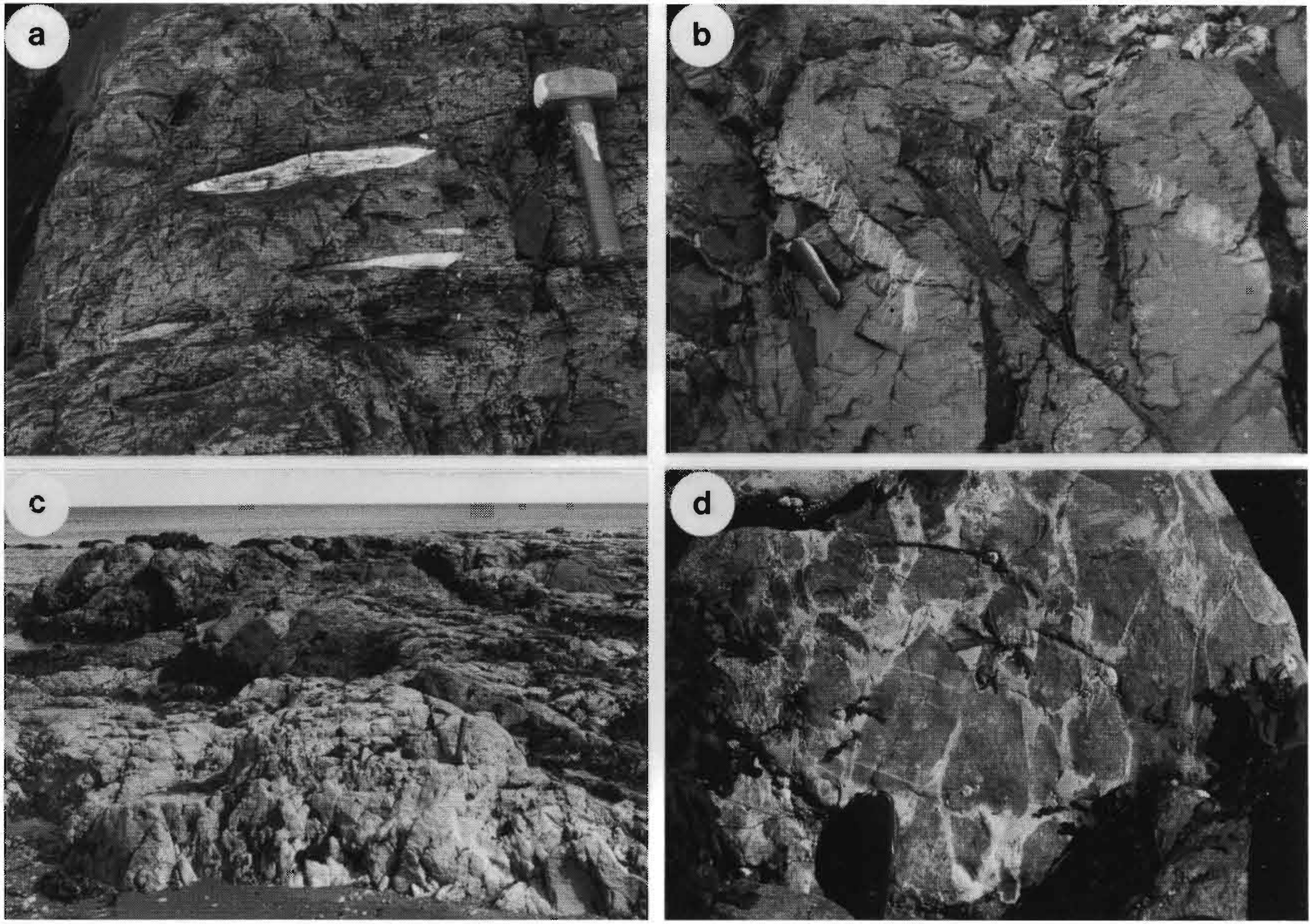

Figure 9. Photographs of rocks showing features of alteration. (a) Lenses of chert in basaltic rocks of Stirling Group. (b) En echelon vein array with tension gashes infilled by epidote hosted by Fourchu Group basalts. (c) Massive chert zone in Fourchu Group volcanics. (d) Flow-top breccia in basalts of Fourchu Group with chert infilling/replacing matrix. Facing page: (e) Epidote alteration zone in basalts of Fourchu Group. (f) Intensely deformed felsic volcanics of the Fourchu Group with chert alteration. Note that the chert-rich zones are relatively competent compared to the relatively unaltered, ductile material that has flowed. (g) Sericite schist with gossan zone due to alteration of disseminated pyrite within the rock. Original rock was fine-grained felsic volcanic of Fourchu Group. (h) Chert alteration as concordant layer (left side of photo) and offshoots that cross-cut layering of volcanics.

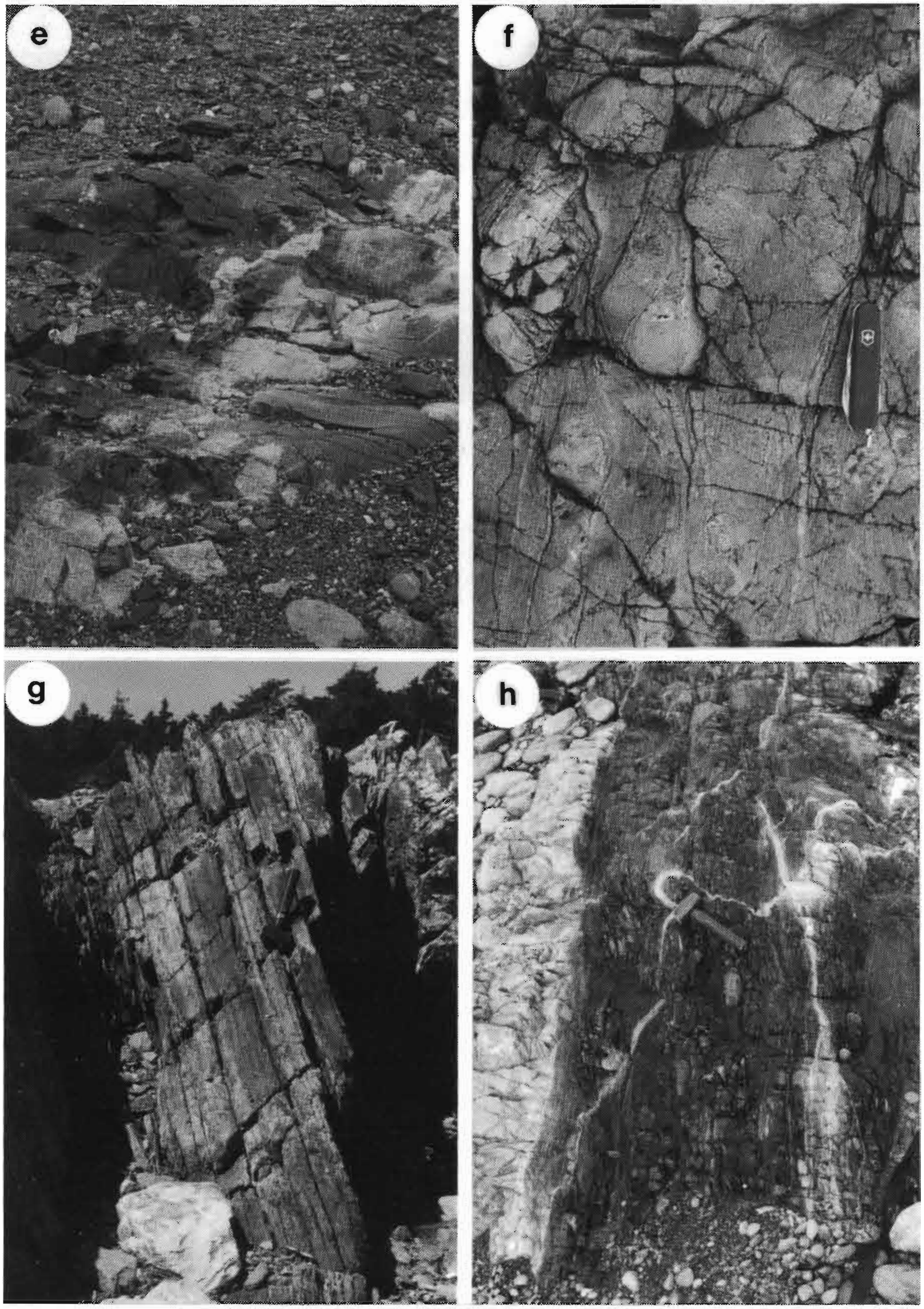
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Table 1. Alteration styles in rocks of southeast Cape Breton Island.

TYPE/ASSOCIATION	NATURE	STYLE	ROCK AFFECTED
Epidote ± carbonate ± silica	generally fine-grained, light to dark green colour; massive; rarely crystalline on fracture surfaces or open spaces	matrix to volcanic breccias (tops, bottoms); en echelon vein arrays; discordant to concordant veins; subparallel fractures; disseminated in matrix of volcanics/ intrusives (petrographic observation) as euhedral grains	dominantly mafic volcanics, lesser abundance in intermediate - felsic volcanics; rarely intrusive rocks; mostly in Fourchu volcanics
Carbonate ± epidote ± silica	coarse carbonate veins ± quartz ± pyrite; veins are en echelon, kinked, variably deformed and multi-generation; fine-grained disseminated in volcanics	disseminated most common; veining less common; very fine-grained type seen petrographically	mafic volcanics and intrusive sheets/dykes/ plugs; volcaniclastic rocks of felsic conposition; rhyolite flows/domes (e.g., Stirling)
Silica ± epidote ± carbonate	massive, fine-grained alteration and quartz veins	pervasive replacement of volcanic rocks of all compositions as variable size/shape zones generally parallel to S_0/S_1; discordant veins, pods and en echelon vein arrays; infilling matrix to volcanic breccia horizons; qtz ± feldspar ± hemetite veins	all volcanic rocks: veins in volcanics and instrusives (feldspar-bearing)
Pyrite ± carbonate ± sericite	fine-grained disseminations, rare coarse cystals	fine disseminations in sericitized shear zones, kink zones; coarse pyrite ± chalcopyrite in carbonate veins	volcanic rocks of all compositions, mafic intrusions
Sericite	alteration zones, fine disseminations	long (10s m), narrow (<3-4 m) lenses or part of kink zones; moderate to intense (90-100% sericite) development; fine disseminations in matrix of volcanics	volcanic rocks of all compositions, but mostly felsic-intermediate
Hematite ± quartz vein	veins and disseminations	quartz-hematite veins in volcanics; disseminated; fine-grained earthy hematite in Capelin Cove granite; flow tops of mafic volcanics	volcanics, mainly felsic; intrusions

types include epidote, carbonate, silica, sulphide, sericite and hematite. Most of the various alteration types occur within close proximity; for example, chert zones are sometimes cored by epidote alteration. Chlorite alteration is present, but its extent is difficult to determine without the benefit of thin sections, thus it is omitted from Table 1 pending further work. However, the following comments are pertinent. Chlorite occurs altering all mafic minerals in the intrusive rocks and is a fine-grained matrix phase in the volcanics. Whereas the other phases are considered to reflect interaction of the host rocks with hydrothermal fluids with production of pervasive alteration zones, chlorite is probably partly due to deuteric alteration and subsequent metamorphism.

The timing of alteration is difficult to constrain, but some generalizations can be made. Sericite-pyrite alteration occurs in high-strain zones (Fig. 9g) and along kink zones; whereas the pyrite is clearly late, the sericite may represent superimposed periods of alteration, although late-stage formation is preferred given its generally discordant nature when examined in detail. Hematite alteration in the Capelin Cove granite is interpreted as early given the association with quartz - red K-feldspar - tourmaline and the open-space infilling textures (Fig. 8d). Epidote and chert/silica (Fig. 9a, c, d, e, f, h) are considered syn-volcanic in most cases for the following reasons: (1) alteration replaces matrix to breccia fragments (Fig. 9d); (2) alteration zones are folded and become boudinaged because of competency contrasts (Fig. 9f); and (3) veins are tightly folded where they cross-cut the fabric (Fig. 9h). However, the fact that abundant quartz and carbonate occur within en echelon vein arrays suggests that some fluid infiltration accompanied late deformation. The occurrence of epidote-rich en echelon vein arrays (Fig. 9b) within epidote-altered volcanics may be interpreted as being either early or later. As with silica and epidote, carbonate is considered to represent several generations of alteration.

Structure

The structural evolution of the study area involved at least two phases of deformation, formation of an array of quartz±carbonate veins, and faulting. Only a brief summary of the observations made are presented below, as a more detailed analysis of the data is required in addition to further field studies. However, the present findings are generally in accord with those of previous workers (Macdonald, 1989; Barr *et al.*, 1996). Understanding the structural history of the area is particularly relevant since the Stirling deposit lies within a shear zone.

The most prominent structural feature is the general northeast trend of bedding (S_0) and cleavage (S_1), although this changes slightly from ca. 45-80° in the south to 10-30° in the north and mimics the trend of the Mira-L'Archeveque Fault Zone (MLFZ, Fig. 1). Structural data for the Main-a-Dieu Group (Fig. 21 in Barr *et al.*, 1996), which lies to the north of the study area, illustrate best the preferred northerly trend of structural elements. The S_1 fabric is axial planar to both micro- and macro-scale folds where observed (Fig. 10a, c) and the folds generally have axes that plunge 0° to 30° toward the northeast or southwest. However, in some areas refolded structures are readily seen (e.g. localities I, J, K in Fig. 1) and it is possible that earlier folds with flat axial planes occur. Orientations of the fold axes of these early folds are highly variable. The lack of an earlier fabric might suggest that either one did not form or that it was poorly developed and has been overprinted or transposed by the more prominent S_1 fabric. The presence and extent of an early period of folding is important with respect to interpreting the stratigraphy of the area and the thickness of units. For example, the measured section at locality I (Fig. 1) has several areas where repetition of units can be related to refolding, thus the true thickness of the section would be overestimated without such knowledge. Given that critical exposures are required, but rarely seen, it is likely that such tectonic thickening is common in the Stirling belt.

Locally there is development of an overprinting fabric (S_2) within areas of high strain, with this prominently displayed at localities A, B, J and the Stirling deposit (Fig. 1). Lack of inland outcrop prevents tracing the lateral extent of these zones. The general orientation of the later shear zones is such that they parallel S_1; at such localities the abundance of veins increases dramatically (Fig. 10d). In some cases CS-type fabrics occur (Fig. 10d) with both dextral and sinistral motion suggested from kinematic indicators. Other kinematic indicators also suggest variable motion.

The most prominent fault in the area is the Mira-L'Archeveque Fault which separates the Stirling and Fourchu groups and extends the length of the study area. Although high strain zones are located close to the fault, areas of very low strain (i.e. localities G, H) are also proximal to the fault. Further work is planned to ascertain the regional influence of this structure.

Mineralization

The study area is characterized by the following types of mineralization: (1) volcanogenic massive sulphides, as

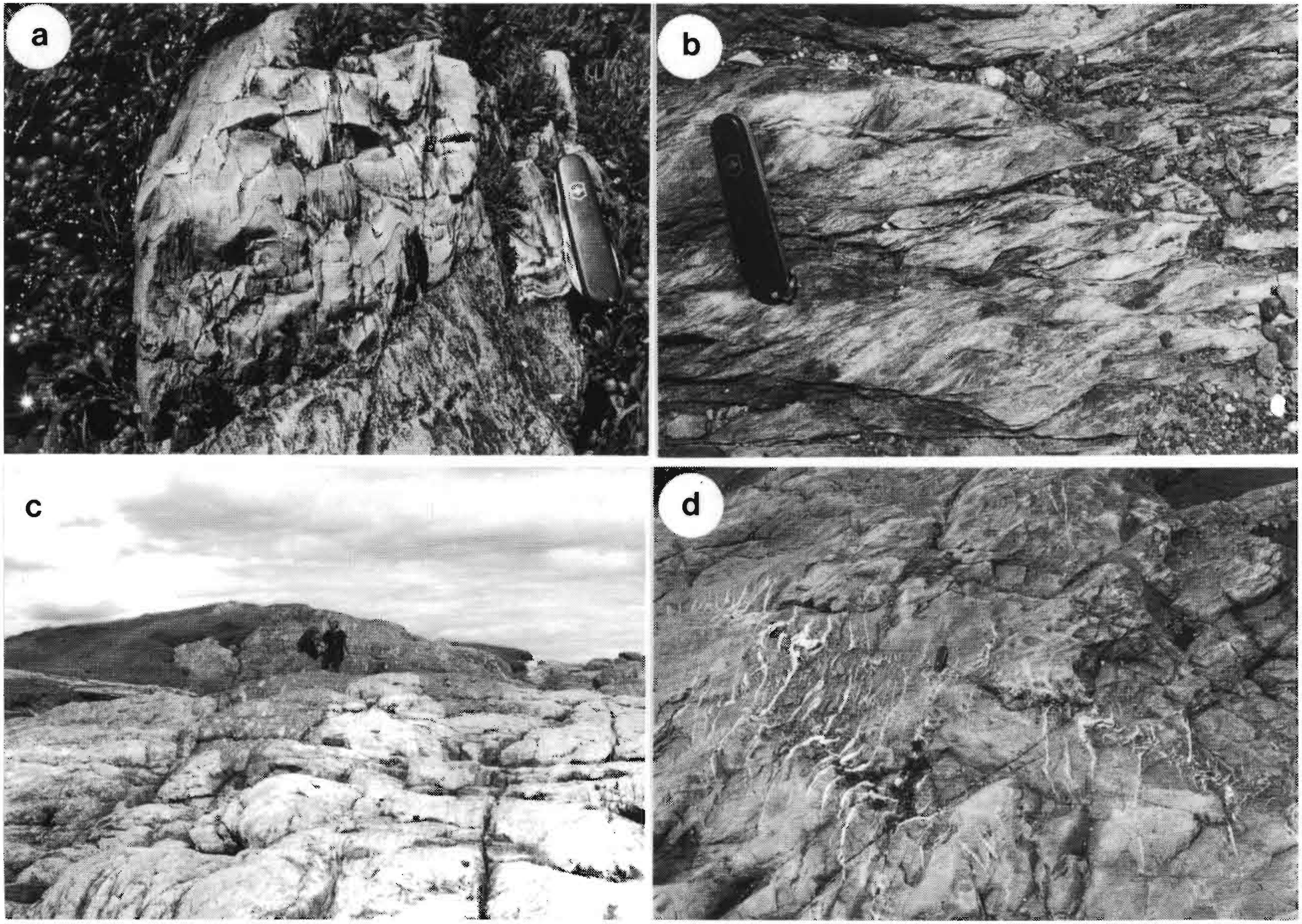


Figure 10. Photographs illustrating some structural features of rocks within the Stirling belt. Photo (a) at Barren Point (locality K in Fig. 1) and photos (b, c, d) at Cape Fourchu (locality J in Fig. 1). (a) Primary bedding (S_0) in fine-grained volcanic sediment/tuff with S_1 oriented perpendicular to bedding, thus indicating an F_1 closure. Fold axis plunges 35° @ 240°. (b) Intensely deformed felsic crystal tuff unit of Forurchu Group showing development of CS fabric with dextral motion. Photo oriented with C fabric (070°) roughly horizontal. (c) Infolding of volcanic units of Fourchu Group (F_1 structure ?) with shear zone to the left and late mafic dyke rock to the right side of photo. (d) Quartz filled extensional shear veins within late kink zone that cuts felsic volcanics of Fourchu Group. S_1 fabric oriented towards northeast of photo (top of photo at 015°). Complementary set of quartz veins for conjugate shear seen in upper part of the photo.

represented by the Stirling Zn-Pb-Cu-Ag-Au deposit (Watson, 1954; Miller, 1979); (2) disseminated pyrite within felsic volcanic rocks or tuffaceous sediments; and (3) quartz-hematite veins that occur within both volcanic and plutonic rocks. The Stirling deposit is described in the next paper in this volume (Kontak, 1998) and only cursory descriptions of the remaining types are given here as geochemical data are pending and further work is planned. Type 2 mineralization occurs as disseminated to massive, euhedral pyrite in felsic and mafic volcanics or tuffs and is best observed along coastal exposures where the gossan zones are readily seen. The zones are tabular in nature (dimensions of ca. 1-3 m thick by 5-20 m in length), but are discordant to layering within the host rocks; in some cases the zones are controlled by cross-cutting structures (e.g. kink zones). Where mineralized zones are hosted by silicic rocks the rock is commonly a sericite schist, whereas abundant chlorite, with or without associated quartz-carbonate veins, occurs in the mafic volcanics that host pyrite.

Quartz-hematite veins occur locally throughout the study area and their abundance varies considerably. In some cases these veins are subparallel to layering in the volcanics, generally northeast-trending, but in other places they are structurally controlled, forming parts of en echelon vein arrays similar to that in Figure 10d. Where such veins occur within the Capelin Cove pluton, the host granite is intensely hematized.

Geochemistry

An extensive geochemical database exists for the study area as a result of previous work, including data for the basaltic rocks of the Stirling and Fourchu groups (Barr *et al.*, 1996) and lithogeochemistry of typical volcanic units in the Stirling Group compiled by Falconbridge Ltd. (Cameron, 1989; Mallinson and Baldwin, 1991). The data offer some insight into the petrogenesis of the volcanic rocks and indicate that alteration or element mobility has occurred within all rock types. Assessment of this data will be used to direct further work in determining the nature of the volcanic rocks in close proximity to mineralized zones following the approaches outlined in Wyman (1996).

Basaltic rocks of the Stirling and Fourchu groups are compared in binary element plots (Fig. 11) and the following points are noted. (1) The slight enrichment of the Stirling volcanics in Cr and Ni suggests a slightly more primitive composition for some of the rocks compared to Fourchu Group basalts. (2) Both groups have high potassic contents for basaltic rocks, but the scatter of data in K_2O versus Zr plots suggests potassium was mobile. The strong correlation of K_2O with Rb suggests that these elements are tied up in secondary mica. (3) The good correlation of Zr with Y, Nb and TiO_2 suggests that these elements have been conserved and may, therefore, potentially be used for petrogenetic interpretation. Thus, the fact that the Stirling Group volcanics appear to have two distinct groupings in the Y-Zr, TiO_2-Zr, and Nb-Zr plots is something that will be investigated.

Representative classification diagrams (Fig. 12) illustrate the following points. (1) The majority of the basic volcanics are subalkaline, but because of alkali mobility some plot in the alkaline field (Fig. 12b) and are tholeiitic based on the FeO/MgO versus silica plot (Fig. 12a). Note, however, that Cameron (1989) classifies most of the Stirling rocks as calc-alkaline and he questions the use of the plots in Figure 12a and b due to potential element mobility. These concerns are valid and will be addressed elsewhere. (2) There is considerable scatter of the data in the ternary plots, particularly for the immobile element plots (e.g., Ti-Zr-Y, Fig. 12e), such that it is not easy to distinguish between different paleo-tectonic settings for the volcanic rocks. Barr *et al.* (1996) and Cameron (1989) also noted this problem. However, the data are consistent with an island arc to calc-alkaline affinity for the basaltic rocks.

Spidergram plots for the same volcanic rocks (Fig. 13), despite the lack of some important elements (e.g. Cs, Th, Ta, U, La, Ce, Hf), indicate the following. (1) The rocks are generally depleted in Nb, which is a signature for subduction zone processes and consistent with an island arc or calc-alkaline affinity. (2) The relatively flat profile for the P to Y part of the plot (HFSE data) is also consistent with the nature of the basaltic magmatism inferred from the discriminant diagrams (Fig. 12).

Binary element plots for the Stirling Group volcanics (Falconbridge data; Fig. 14) indicate a continuum in silica from ca. 40 to 80 wt. %, which contrasts markedly with the distinct bimodal nature of the volcanics based on the data set in Barr *et al.* (1996) and is interpreted to indicate mobility of silica. Cameron (1989), while realizing that silicification occurred, nevertheless interpreted the continuum of chemistry as being a primary feature of the rocks, a conclusion this writer does not concur with. The scatter of data for the alkalies (Na_2O and K_2O) also reflects element mobility and contrasts with the more uniform trends for CaO, MgO and Fe_2O_3 in the Harker-type plots, which supports use of some of the plots in Figure 12, although there is clearly depletion of some samples in CaO. The data also indicate enrichment of some samples in P_2O_5 which may reflect formation of

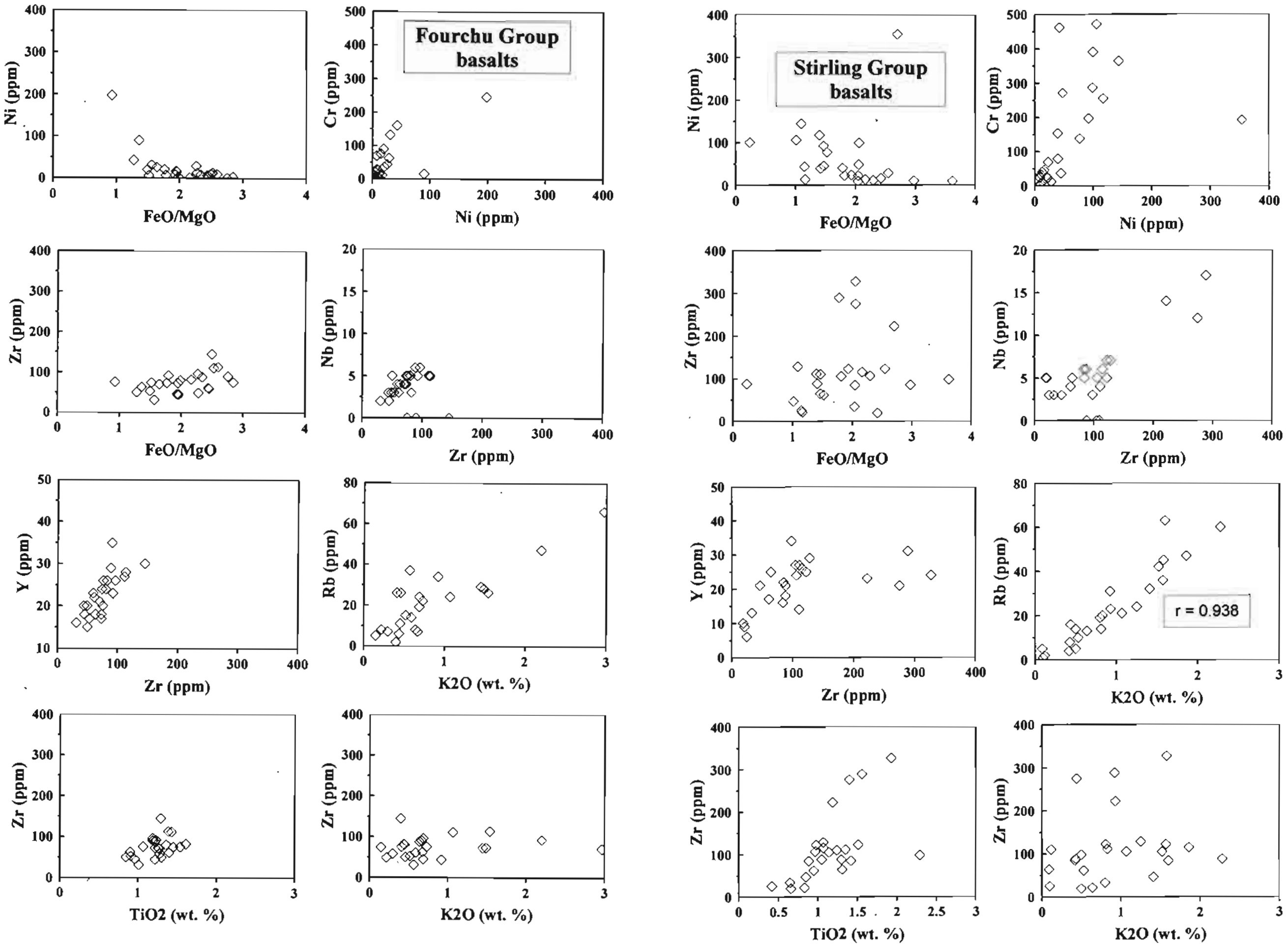


Figure 11. Binary element plots for basalts of the Fourchu and Stirling groups (data from Barr *et al.*, 1996). Note that the scales on the plots are the same for both groups of rocks to facilitate comparison. See text for discussion

secondary phosphate minerals which, interestingly, has been documented in some volcanogenic massive sulphide deposit areas (Schandl and Gordon, 1991; Schandl *et al.*, 1995). Finally, the large variation in trace elements Sr, Rb and Zr may also indicate element mobility or primary variations resulting from different petrogenetic processes.

Discussion and Focus of Future Work

Preliminary results of field and laboratory work that has focused on the Late Hadrynian volcanic-plutonic rocks of the Stirling area of southeast Cape Breton indicate that these suites likely represent products of bimodal magmatism within continental margin arcs and that considerable post-crystallization interaction with fluids has occurred. This work supports the conclusions of Barr *et al.* (1996) in terms of the general paleo-tectonic setting of the rocks, but more detailed petrochemical work is required in order to define more precisely the setting in terms of current ideas pertaining to magmatism (Wyman, 1996). In addition, the nature and extent of alteration requires more attention, as the initial results of this study combined with examination of the existing database suggests that chemical modification of the magmatic rocks is potentially more extensive than previously considered and, as such, has implications with regard to the use of discriminant diagrams (e.g. Fig. 12). Carefully collected sample suites from measured sections will be used to address these problems.

The structural evolution of the study area has received only a cursory overview. From the work of Macdonald (1989), Barr *et al.* (1996), and this study it is apparent that several episodes of highly variable strain have affected the area. This deformation must have caused some tectonic thickening and modification of original stratigraphic relationships which hitherto has not been considered in terms of the regional geology. This aspect of the geology must be addressed in the context of mineral exploration. In addition, the significance of major

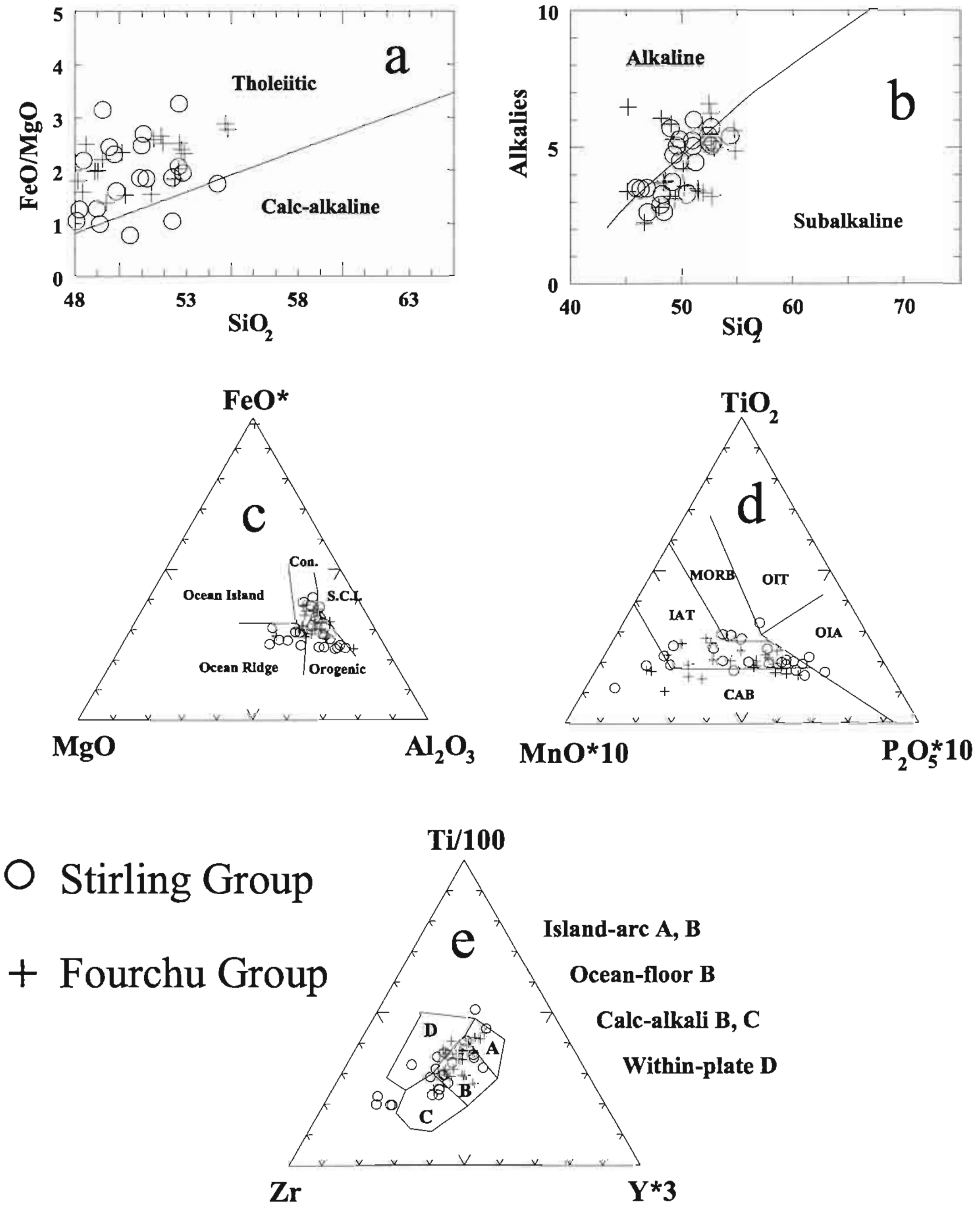
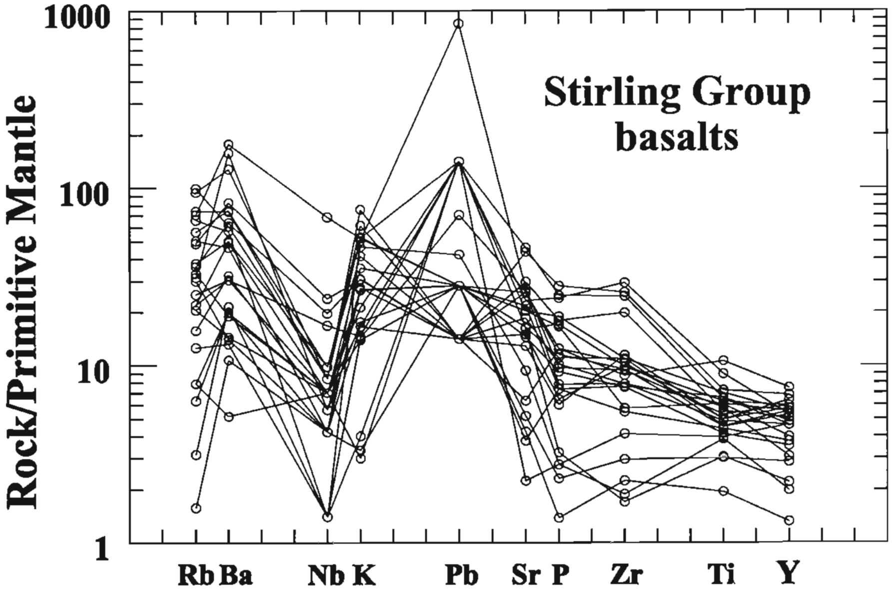


Figure 12. Discriminant plots for basalts of the Stirling and Fourchu groups (data from Barr *et al.*, 1966). Note that the data fall in the tholeiitic field, straddle the alkaline-subalkaline dividing line, and are scattered in the triangular plots with analyses plotting in different paleotectonic fields, as discussed in the text.

faults in the study area (e.g. Mira-L'Archeveque Fault), especially their time of formation, offsets, and other structural data, remains to be addressed and will be the focus of future work.

Rocks in the area have been affected by both synvolcanic and epigenetic phases of mineralization. The main focus of future work will be directed at (1) the potential for precious metals associated with zones of pyrite-sericite-chlorite alteration and quartz-hematite veins, and (2) the nature of massive sulphide mineralization at the Stirling deposit, with particular attention to the potential for further deposits.



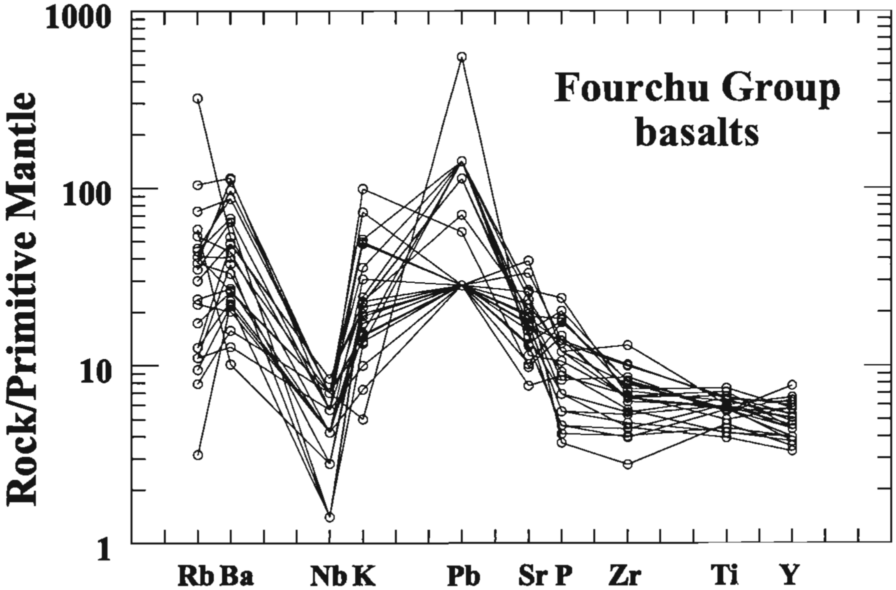


Figure 13. Partial spidergram plots for basalts of the Stirling and Fourchu groups (data from Barr *et al.*, 1996). See text for discussion.

Acknowledgments

This project benefitted immensely from the cooperation of S. M. Barr and A. S. Macdonald, who freely shared their expertise on the geology of the study area and provided field maps and notes from their earlier work. The very capable assistance of Andrea Hulshof in the office and field contributed significantly to the success of the field season and the project.

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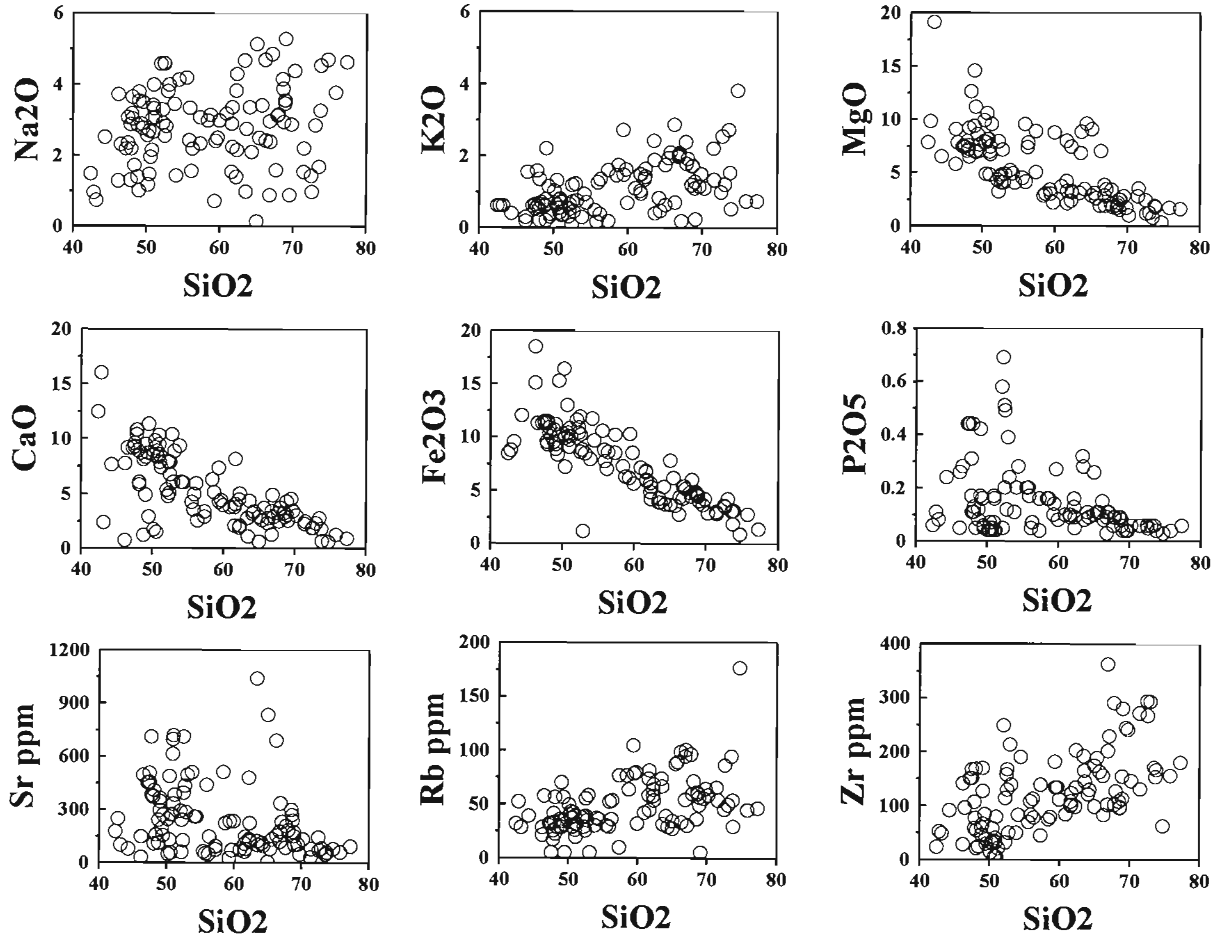

Figure 14. Binary element plots for geochemical data of Stirling Group volcanics (data from Mallinson and Baldwin, 1991). Note that the data show a continuum in terms of silica and that for many elements (Na, K, Ca, P, Sr, Rb, Zr) there is a scatter that suggests element mobility.

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