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GEOLOGY, ALTERATION ASSEMBLAGES AND GEOCHEMISTRY OF THE DUDER LAKE GOLD SHOWINGS, NORTHEASTERN NEWFOUNDLAND

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ABSTRACT

In the early 1980's, the emphasis on exploration in the eastern Dunnage Zone shifted from base metals to gold mineralization, with the discovery of quartz-vein-hosted gold mineralization in the Jonathan's Pond area. One of the more significant discoveries, located at Duder Lake, comprises structurally controlled mesothermal-style gold mineralization hosted by gabbros (Corvette, Goldstash, Flirt) and graphitic sedimentary rocks (Stinger).

Bedrock in the study area consists of two northeast-trending sedimentary (Davidsville Group) and sedimentary–volcanic (Botwood Group) units. The Ordovician–Silurian Davidsville Group underlies the eastern part of the study area and is in fault contact with the Silurian Botwood Group to the west. Small gabbroic to dioritic sills and dykes intrude both groups. Mineralization, for the most part, is confined to gabbros that have intruded the Davidsville Group proximal to its fault contact with the Botwood Group. One zone of gold mineralization (Flirt) is hosted by gabbro intruding the Botwood Group distal to the fault contact.

The gabbroic host rocks exhibit a progressive hydrothermal alteration, superimposed on low-angle Riedel shears, which ranges from regional greenschist-facies metamorphic assemblages to intense hydrothermal alteration assemblages dominated by sericite, Mg-chlorite, ankerite–siderite, abundant pyrite and arsenopyrite, and locally gold. Mineralized grab samples locally exceed 30 000 ppb gold and in excess of 70 000 ppm arsenic.

Progressive alteration is also reflected by major-, trace-, and rare-earth-element geochemistry. There are major additions of CO_2, CaO, alkalis, Au, As, Sb, and minor enrichment in the LREEs. These changes are attributed to temporally and spatially changing CO_2/H_2O and water/rock ratios.

Geological, mineralogical, and geochemical relationships suggest that the mineralizing fluids may have been derived from metamorphic devolatilization of a deep crustal source inferred to be Gander Zone basement rocks.

INTRODUCTION

Since the discovery of quartz-vein-hosted auriferous mineralization in the Jonathan's Pond area (Blackwood, 1982), rocks of the eastern Dunnage Zone have been the focus of extensive gold exploration. Numerous mesothermal-style gold occurrences and several epithermal-style alteration zones were discovered as a result of this exploration.

In 1988, structurally controlled mesothermal-style gold mineralization was discovered near Duder Lake (Figure 1) by Noranda Exploration Company Limited. Noranda has undertaken detailed soil-geochemistry surveys, geological mapping, trenching, and limited diamond drilling to delineate several zones of mineralization (Figure 2) (Green, 1989; Tallman, 1990). Three distinct styles of mineralization are present: (1) gabbro-hosted, shear-controlled sulphide disseminations (Goldstash and Corvette), (2) gabbro-hosted quartz veins (Flirt), and (3) sediment-hosted, shear-controlled quartz veins (Stinger) (Tallman, 1990).

This project forms part of an M.Sc. study that was initiated in the summer of 1991 in conjunction with a regional gold-metallogeny program carried out by the Newfoundland Department of Mines and Energy under the Canada–Newfoundland Mineral Development Agreement (1989–1994) (cf. Evans, 1991, 1992; Churchill and Evans, 1992). The study will examine alteration systematics associated with gold mineralization, geochemistry of fresh versus altered and mineralized rocks and suggest a genetic model for gold

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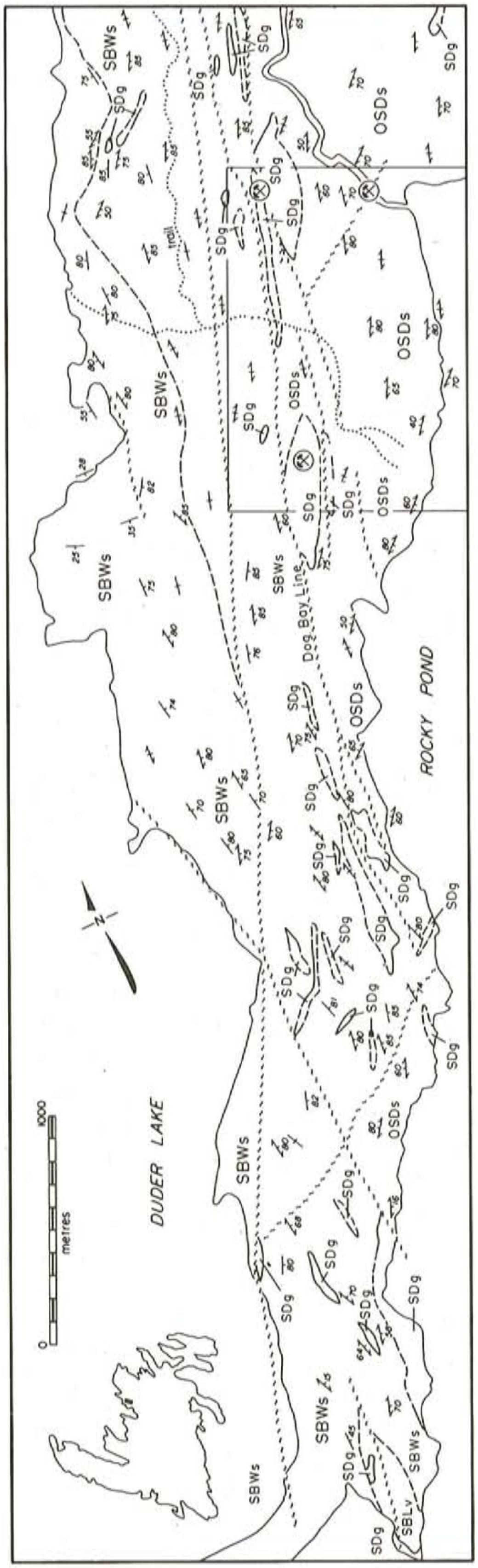


LEGEND

SILURIAN TO DEVONIAN

SDg — *Medium- to coarse-grained gabbroic, dioritic, and diabasic sills and dykes locally posessing pegmatitic textures and primary igneous layering. Intrusive bodies, variably hydrothermally altered, overprinting regional greenschist-metamorphic assmblages. Intense hydrothermal alteration correlative with elevated gold abundances*

SILURIAN

BOTWOOD GROUP

Wigwam Formation

SBWs — *Siliceous and micaceous, red to green, massive to laminated shallow-water sandstone and minor siltstone having locally developed weak to moderate S_2 cleavage. Down-section, rocks change to deeper-water siltstone, argillaceous siltstone, and shale. Massive units up to 25 m in thickness locally, otherwise thinly bedded. Moderate to strong cleavage developed throughout*

Lawrenceton Formation

SBLv — *Subaerial, scoriaceous, purple to black basalt flows, pillows and breccias*

ORDOVICIAN TO SILURIAN

DAVIDSVILLE GROUP

OSDs — *Dark-grey, green, and black slate associated with minor argillaceous siltstone and fine-grained carbonaceous sandstone. Thinly interbedded and exhibiting a strong penetrative slaty cleavage*

Contact (defined, approximate)
Faults
Bedding (inclined, vertical)
S_2 Schistosity (inclined, vertical)
Drill Road
Gold Mineralization

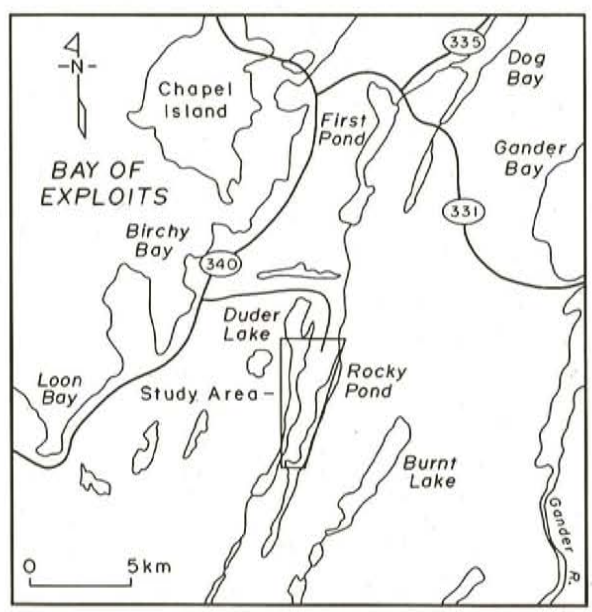


Figure 1. *Major geological units in the Duder Lake area, showing location of gold prospects. Rectangle delineates the area shown in Figure 2. Modified from Noranda Exploration Company Limited maps (Green, 1989; Tallman, 1990).*

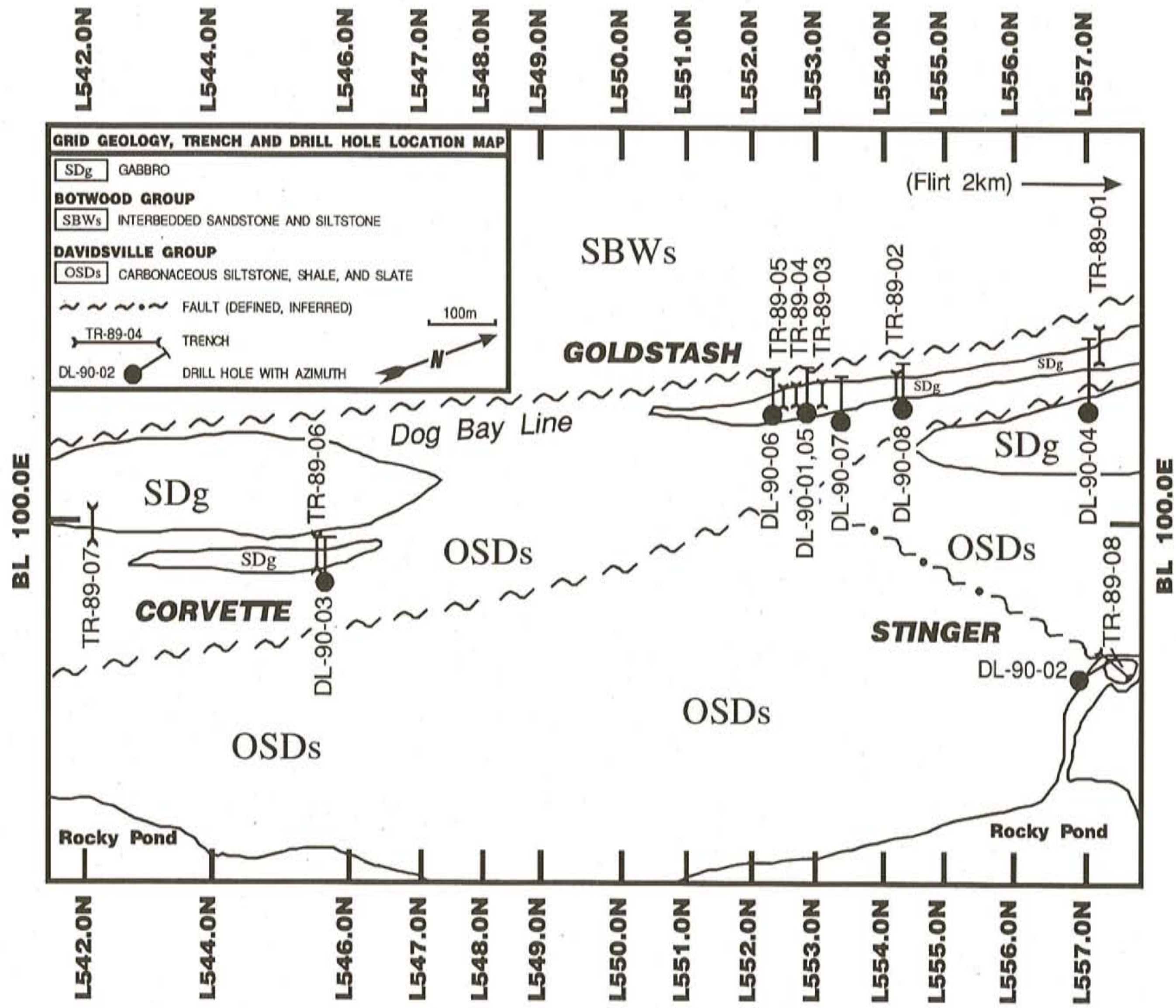


Figure 2. *Simplified geology, drillhole and trench location map for the Stinger, Goldstash, and Corvette prospects. Modified from Noranda Exploration Company Limited maps (Green, 1989; Tallman, 1990).*

mineralization at Duder Lake that could be pertinent to showings elsewhere in the eastern Dunnage Zone.

For a comprehensive review of previous work and the regional geological setting, the reader is referred to Churchill and Evans (1992).

REVIEW AND REGIONAL SETTING

Duder Lake is located in the eastern Dunnage Zone of the Newfoundland Appalachians (Williams *et al.*, 1988). The Dunnage Zone records the evolution, and subsequent destruction, of the Paleozoic Iapetus Ocean and, as such, the geological history can be subdivided into two stages: pre-accretion and post-accretion.

1) Pre-accretionary volcanism and pre- to syn-accretionary sedimentary rocks were deposited in Cambrian to Middle Ordovician island-arcs and back-arc basins: e.g., Gander River Complex (O'Neill, 1991); Davidsville Group (Kennedy and McGonigal, 1972); and the Exploits Group (Helwig, 1969). Late Ordovician to Early Silurian closure of the Paleozoic Iapetus Ocean resulted in flyschoid-sediment deposition in fault-bounded basins of the east-central Dunnage Zone (Dean, 1978; Kean *et al.*, 1981; Szybinski *et al.*, 1990).

2) Post-accretionary events included deposition of Silurian subaerial fluviatile to shallow-marine sediments and epicontinental-style volcanism (Coyle and Strong, 1987); e.g., Botwood Group (Williams, 1962). Widespread deformation and plutonism in the

eastern Dunnage Zone, originally thought to be related to Acadian deformation, is now thought to have resulted from a Silurian event (Dunning *et al.*, 1990).

GEOLOGY

The geology of the Duder Lake area is dominated by two north–south-trending sedimentary and sedimentary–volcanic units (Figure 1). The western part of the map area is underlain by sedimentary and volcanic rocks of the Silurian Botwood Group whereas the eastern part is underlain by sedimentary rocks of the Davidsville Group, which are Ordovician to Early Silurian in age. The sedimentary and volcanic rocks record three different deformational events; only faulted contacts are observed between the Botwood and Davidsville groups in this area. Numerous, small, Siluro-Devonian(?) gabbroic dykes and sills intrude both groups proximal to their faulted contact, which is informally named the Dog Bay Line (Hank Williams, personal communication, 1992). Some of these gabbros contain epigenetic, shear-controlled gold mineralization.

DAVIDSVILLE GROUP

This unit is characterized by undivided grey to black slate and/or shale, sandstone, siltstone, greywacke, and argillaceous siltstone (Plate 1). The Davidsville Group has an island-arc provenance and consists of thinly bedded turbidites and contourites, which were fed by arc systems located to the northwest (Blackwood, 1982). The Stinger prospect, found in graphitic siltstones of the Davidsville Group, is the only known sedimentary-hosted, shear-controlled gold mineralization in the Duder Lake area.

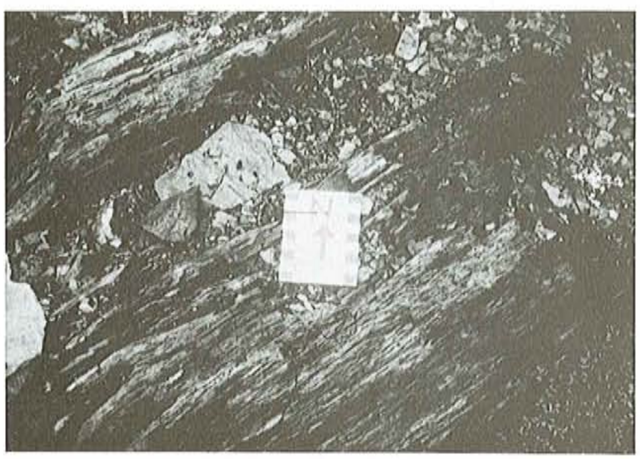


Plate 1. *Graphitic siltstones and shales of the Davidsville Group near the Goldstash Prospect. Note northeast-trending slaty cleavage (S_2).*

BOTWOOD GROUP

The Botwood Group consists of three formations–the basal conglomeratic Goldson Formation, a middle terrestrial volcanic unit named the Lawrenceton Formation, and an upper red sandstone unit called the Wigwam Formation (Williams, 1972). At Duder Lake, only the Lawrenceton and Wigwam formations are present.

Lawrenceton Formation

Subaerial to terrestrial volcanic rocks outcrop in the southern part of the map area and are faulted against the Wigwam Formation. These rocks comprise purple to black vesicular and amygdaloidal pillow basalts, breccias, and flows (Plate 2). Although the contact is faulted, it may originally have been conformable with the base of the Wigwam Formation such as seen west of the Duder Lake area.

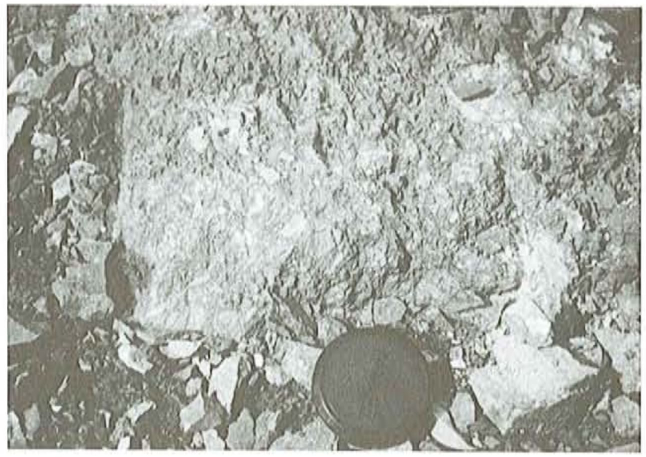


Plate 2. *Agglomerate of the Lawrenceton Formation of the Botwood Group.*

Wigwam Formation

The Wigwam Formation is the most prominent unit in the area consisting of undivided micaceous and siliceous, red, brown, grey and green siltstone, sandstone, and shale (Plate 3). Minor, thin, tuffaceous horizons have also been observed in rocks of the Wigwam Formation east of Duder Lake.

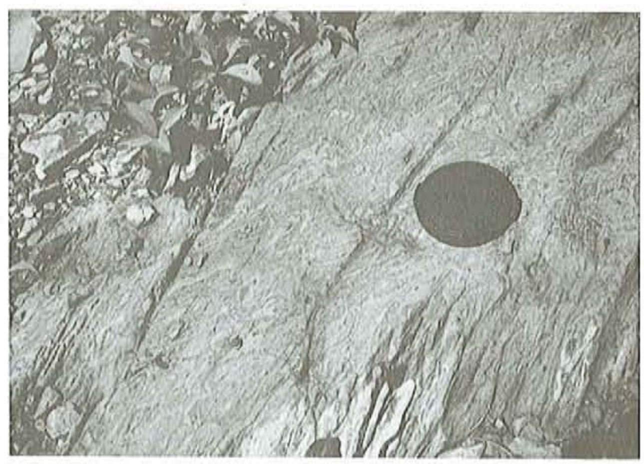


Plate 3. *Convoluted-bedded, fine-grained sandstones of the Wigwam Formation possessing strong S_2 cleavage.*

An east–west transect across the Wigwam Formation shows a gradual facies change from subaerial red beds to deeper water siltstones, argillaceous siltstones and shales. This change is demonstrated by a gradual colour change from reddish brown, through greenish, to grey. In addition, the detrital mica content of the Wigwam Formation diminishes eastward. The gradual increase in detrital mica to the west, inferred to be derived from metamorphic rocks of the Gander Zone, and the facies change from deep to shallow water, suggests an original conformable contact between the Davidsville and Botwood groups.

MAFIC DYKES AND SILLS

Numerous small, fine- to coarse-grained gabbroic to dioritic dykes and sills of probable Late Silurian–Early Devonian age intrude both the Davidsville and Botwood groups proximal to the Dog Bay Line (Figures 1 and 2). The number of dykes and sills diminishes with increasing distance from the fault contact. All intrusions are orientated sub-parallel to parallel to the northeast–southwest-trending linears that transect the area. Similar observations have been made by Evans (1991), who noted that gabbros proximal to these linears have evidence for rotation into the plane of shear (e.g., Clutha prospect) suggesting pre- to syndeformation emplacement. No constraints on either the age of deformation or intrusion of the gabbros exist so exact temporal relationships are not known. Drillcore samples of gabbro, which host the Goldstash and Corvette prospects, have chilled margins and the host sedimentary rocks are hornfelsed proving the intrusive relationships. Gabbros are variable compositionally from leucocratic to melanocratic and texturally from fine to coarse grained (Plate 4).

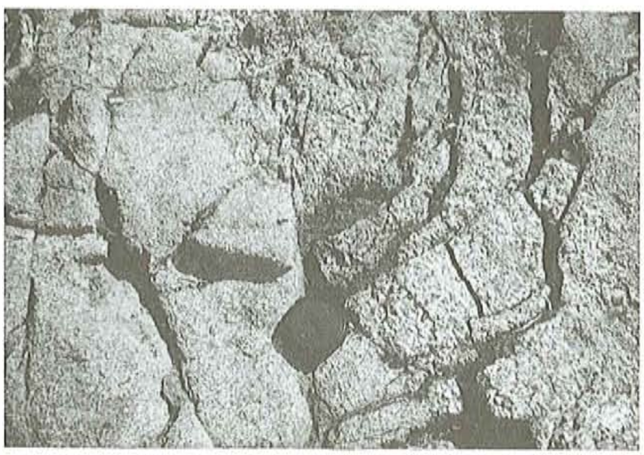


Plate 4. *Coarse-grained gabbro found in red beds of the Wigwam Formation approximately 3 km northeast of the northern end of Duder Lake.*

These gabbros probably represent partial melts of lower crustal material produced by either frictional heating along activated or re-activated structures and/or thickening of the crust due to transpressional movement during the Silurian. Blackwood (1982) observed gabbros having similar geological relationships in the Gander Lake area to the south and suggested that they have a Mount Peyton affinity (cf. Strong, 1972).

DEFORMATIONAL FABRICS

Structural studies by Karlstrom *et al.* (1982) of the Indian Islands and Botwood groups north of Duder Lake on the Port Albert Peninsula, found evidence for three periods of deformation. These three deformational events defined by folding and re-folding of pre-existing structures are:

1) D_1, structures that are generally isoclinal intrafolial folds and not easily distinguishable;

2) D_2, structures that are strongly asymmetrically folded having northeast-trending S_2 cleavages that dip moderately to steeply southeast and refold pre-existing D_1 structures; they are the most dominant structural features present, and

3) D_3, structures that include those that crenulate or fold the S_2 cleavage.

Evidence of these three deformational events are also preserved in the rocks at Duder Lake.

The D_1 deformational fabrics are locally preserved as overturned beds and small recumbent folds that dip steeply to the southeast (Plate 5). The F_1 structures have been inferred to be broad regional-scale folds that were recumbent prior to the F_2 folding (Karlstrom *et al.*, 1982) and either did not have a well-developed cleavage or had a cleavage that was widely spaced.

Plate 5. *Overturned F_1 fold in argillaceous siltstones of the lower part of the Wigwam Formation.*

The main D_2 deformational fabric is recognized as a prominent, well-developed penetrative cleavage (S_2), which is axial planar to F_2 folds (Plate 6). Lower hemisphere stereographic projections (Figure 3a, b) of the structural data indicate that the cleavage is northeast-trending having variable inclinations from shallowly dipping to sub-vertical. The

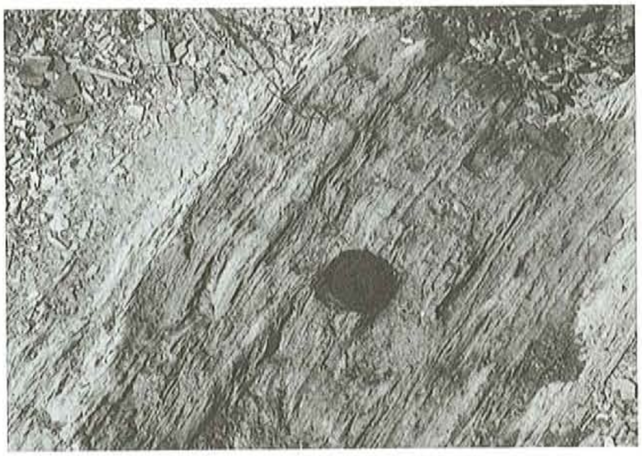


Plate 6. *Northeasterly trending D_2 fabric developed in greenish siltstones of the lower part of the Wigwam Formation.*

bedding-plane data (S_0) are quite varied in orientation and dip, however, a π-girdle can be constructed through the data points inferring a gently plunging fold axis to the south (Figure 3c). Comparing the two plots, it is apparent that the cleavage is axial planar to the folding, reaffirming the regional structural relationships defined by Karlstrom *et al.* (1982).

The D_3 deformational fabrics are only seen locally and manifested as kinking and crenulation of the S_2 cleavage (Plate 7). The S_3 cleavage planes are widely spaced (up to 10 cm) and only observed in rocks of the Wigwam Formation. Although the S_3 fabrics are not observed in rocks of the Davidsville Group, overall similarities in structural style between both groups suggest the same deformation events affected both. The orientations of the S_3 data are quite varied (Figure 3d) and are locally preserved. Such observation suggests that its development may in part be controlled by competency contrasts in the rock units.

Brittle-ductile, low-angle Riedel shear zones are inferred to be second- or third-order structures originating from the Dog Bay Line that have widths up to 3 m and variable lateral extent from several metres to hundreds of metres. The development of these shear zones may be related to the D_2 and/or D_3 deformational events.

ALTERATION STUDIES

Alteration and mineralization are shear-controlled and can be observed in both gabbroic and graphitic sedimentary rocks. The hydrothermal alteration overprints a low- to mid-greenschist-facies metamorphic assemblage, which is totally obliterated in intense alteration zones found proximal to the shear zones.

Alteration in Sedimentary Rocks

Alteration in sedimentary rocks is confined to narrow margins (up to 2 m wide) in host siltstones proximal to shear-parallel quartz–carbonate veins. The narrow alteration haloes envelop auriferous, sulphide-bearing quartz–ankerite–siderite veins (up to 30 cm wide) having a mineralogy comprised predominantly of sericite–ankerite–siderite–±pyrite±arsenopyrite.

Alteration in Gabbro

Gabbro-hosted alteration can be subdivided on the basis of alteration intensity and mineralogical changes into two zones: progressively hydrothermally altered gabbros (PHA-Zone), and mineralized gabbros (MG-Zone). The two zones are transitional with one another and reflect a gradual loss in alteration intensity away from the shear zone. The alteration overprints a pre-existing low- to mid-greenschist-facies metamorphic assemblage (GMA-Zone). Distinct mineralogical assemblages and geochemical signatures are observed for both alteration types as well as the regional greenschist metamorphic facies (Figure 4). The alteration progression observed in both sedimentary and gabbroic rocks has parallels to the alteration zoning documented by Lowell and Guilbert (1970) from hydrothermal porphyry systems.

Fresh Gabbro (GMA-Zone)

The term 'fresh' is a descriptive term used in comparison to the hydrothermally altered gabbros. These rocks were subjected to lower- to mid-greenschist-facies metamorphism and as a result contain typical metamorphic mineral assemblages. Major phases include relatively fresh, euhedral, locally uralitized clinopyroxene (Plate 8); abundant albitized plagioclase; calcitic veinlets, patches, and alteration of plagioclase; and Fe-rich chlorite (clinochlore?). Leucoxene and other amorphous Ti-bearing phases are common and were derived from the breakdown of ilmenite and/or titaniferous magnetite. Minor epidote is present as an extremely fine-grained constituent of the groundmass. The GMA-Zone transitionally grades into the PHA-Zone over distances of 2 to 3 m.

Progressive Alteration Zone (PHA-Zone)

Gabbro within the progressive alteration zone was subjected to varying intensities of hydrothermal alteration that produced bulk geochemical and mineralogical change. The greenschist-facies metamorphic assemblage is gradually replaced by the hydrothermal alteration assemblage that increases in intensity toward mineralized sections. This zone is a hybrid because it possesses characteristics of both the GMA- and MG-Zones. Major mineralogical changes observed include changes in carbonate and chlorite mineralogy from regional metamorphic phases to hydrothermal phases. Carbonate chemistry changes from calcite to ankerite–siderite-rich, and chlorite chemistry becomes progressively Mg-rich (Figure 5). This relationship is sympathetic because the Fe required for the development of ankerite–siderite is probably derived from the breakdown of clinochlore to produce penninite–the Mg-end member. The appearance of penninite is a result of contemporaneous Fe-loss and resulting Mg-enrichment where the increase in

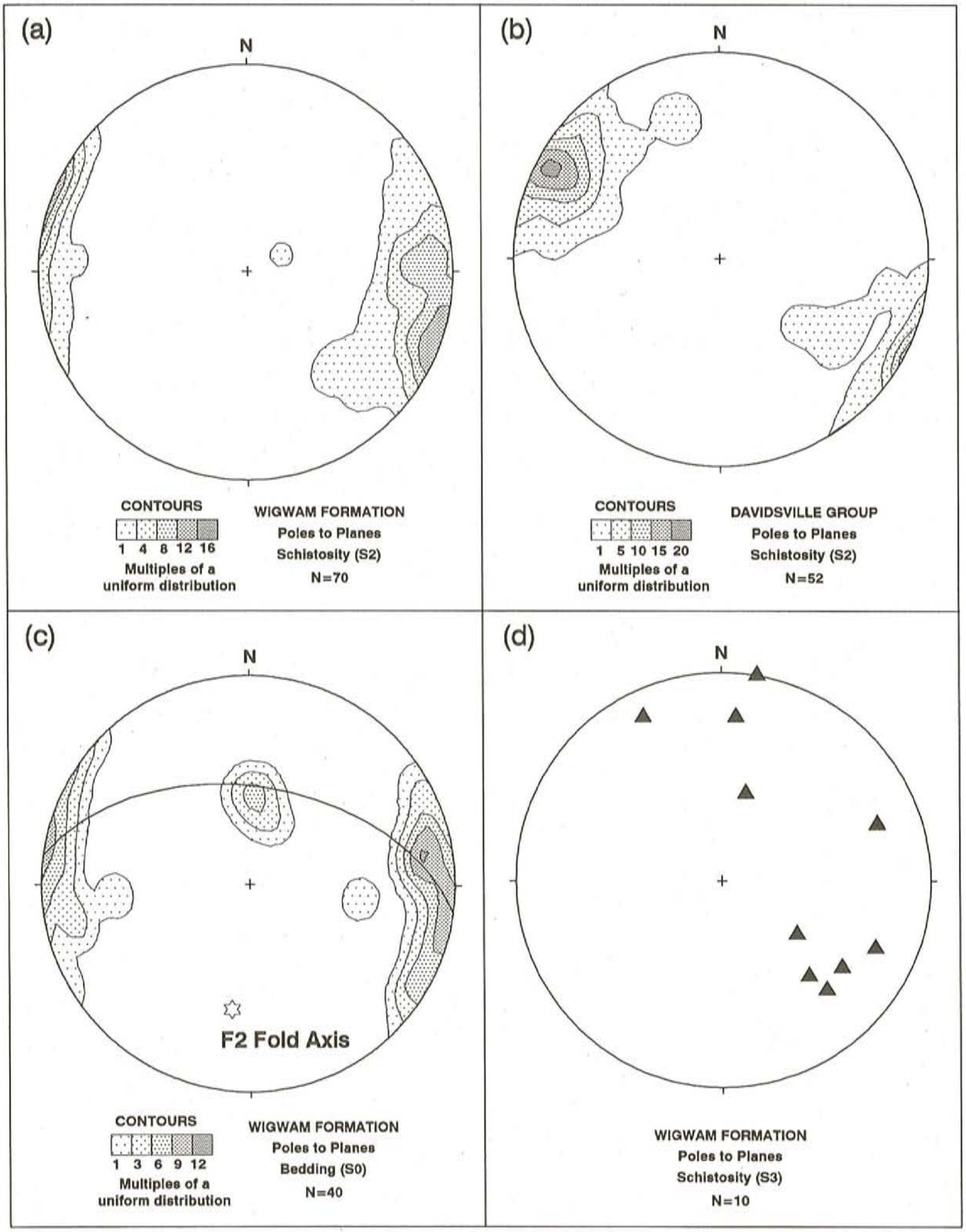


Figure 3. *Lower hemisphere projections for bedding and cleavage data. (a) S_2 cleavage data from the Wigwam Formation illustrating the dominant northeast-trending cleavage. (b) S_2 cleavage data for the Davidsville Group showing strong northeast-trending orientation differing slightly from that of (a). May be attributable to rigid block rotation postdating cleavage development. (c) Bedding data for the Wigwam Formation. π-girdle identifies an F_2 fold axis with moderate south-southwest plunge. (d) S_3 cleavage data from rocks of the Wigwam Formation showing variable orientations.*

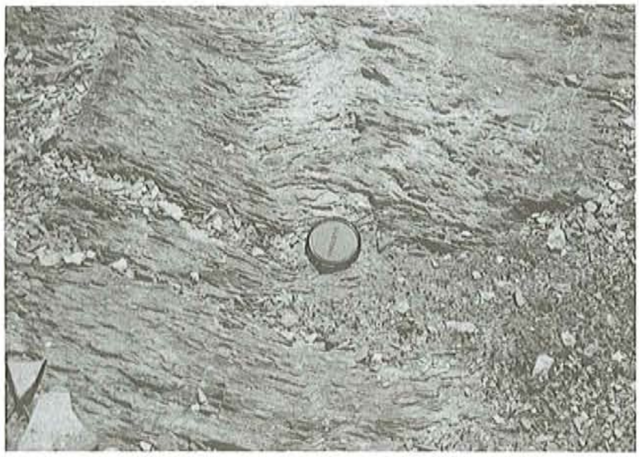


Plate 7. *S_3 crenulation cleavage kinking S_2 cleavage developed in maroon-coloured sandstones of the Wigwam Formation.*

Mg is a relative phenomenon (Plate 9). Other changes in this zone include the appearance of sericite, which increases in abundance toward the mineralized zone, and the gradual destruction of primary igneous phases such as pyroxene and ilmenite.

The PHA-Zone passes gradationally into the mineralized zone, which is delineated by increased sulphide abundance and a well-developed gossan halo.

Mineralized Zone (MG-Zone)

The mineralized zone is the strongest hydrothermal alteration zone and as a result, has a mineral assemblage that differs greatly from the greenschist assemblage. This zone is characterized by intense Fe-carbonatization, sulphidation, and usually has the strongest deformation (Figure 4). The alteration assemblage includes sericite, penninite, arsenopyrite, pyrite, ankerite–siderite and quartz. The intense alteration is illustrated by the almost complete destruction of primary igneous minerals such as pyroxene and magnetite (Plate 10).

GOLD MINERALIZATION

Gold mineralization at Duder Lake is similar to mesothermal-style mineralization and is hosted by gabbroic and sedimentary rocks. Gabbro-hosted mineralization can be subdivided into two groups:

(1) shear-controlled sulphide disseminations in host gabbro (e.g., Goldstash and Corvette) and,

(2) shear-controlled quartz–carbonate veins containing sulphides and minor gold (e.g., Flirt).

Group 1 mineralization is associated with wall-rock replacement during hydrothermal alteration with the addition of pyrite and arsenopyrite, both of which host the gold in the sulphide crystal structure. This group contains the previously described alteration zonations.

Group 2 mineralization is vein-hosted and comprises thin (<5 cm) quartz–carbonate veins containing patchy sulphides and gold. Sericite–chlorite–carbonate alteration is confined to narrow zones along the vein margins and do not contain abundant sulphides.

Shear-controlled, sedimentary-rock-hosted mineralization occurs at Stinger in the rocks of the Davidsville Group. The style of mineralization observed at Stinger is similar to that observed at Flirt but veins are usually thicker (up to 20 cm) having wider alteration haloes and stronger alteration.

GEOCHEMISTRY

Seventy-two samples were collected for geochemical analyses. Of these, 58 samples are gabbros (from GMA-, PHA-, and MG-Zones), 11 samples are sedimentary rocks hosting gabbros (two of which were from the Stinger prospect), and 3 samples of subaerial basalt flows (two from the Duder Lake area and one 20 km south of Duder Lake). The basalts were collected from a wide area to ascertain whether they are genetically related to gabbro plutonism or represent a separate phase of volcanism because age relationships between the two are unknown.

Sedimentary Rocks

Sedimentary rock samples were collected to ascertain if the alteration haloes associated with the Riedel shears are solely confined to the gabbros or extended into the sedimentary host rocks. In addition, samples were taken from Stinger to characterize the alteration and mineralization.

The sedimentary rocks defined a passive margin setting on the tectonic discrimination diagram of Roser and Korsch (1986) as would be expected from the tectonic setting inferred for both the Davidsville and Botwood groups (Figure 6).

Volcanic Rocks

The trace-element data based on the tectonic discrimination diagram of Pearce and Norry (1979) infer a within-plate setting. Such a petrogenetic model is supported by the regional tectonic interpretations for these volcanic rocks (Figure 7a).

The chondrite-normalized rare-earth and trace-element compositions of the basalts (Figure 7b) have a typical continental-type morphology with the characteristic LREE enrichment and HREE depletion (cf. Haskin *et al.*, 1966; Henderson, 1984). The LREE's are enriched from 11 to 100 X chondrite and the HREE's from 7 to 11 X chondrite. The sample that is depleted in Th and slightly enriched in all REE's relative to the other samples, has been hydrothermally altered and contains a secondary alteration assemblage of chlorite and minor carbonate and sericite. However, it still

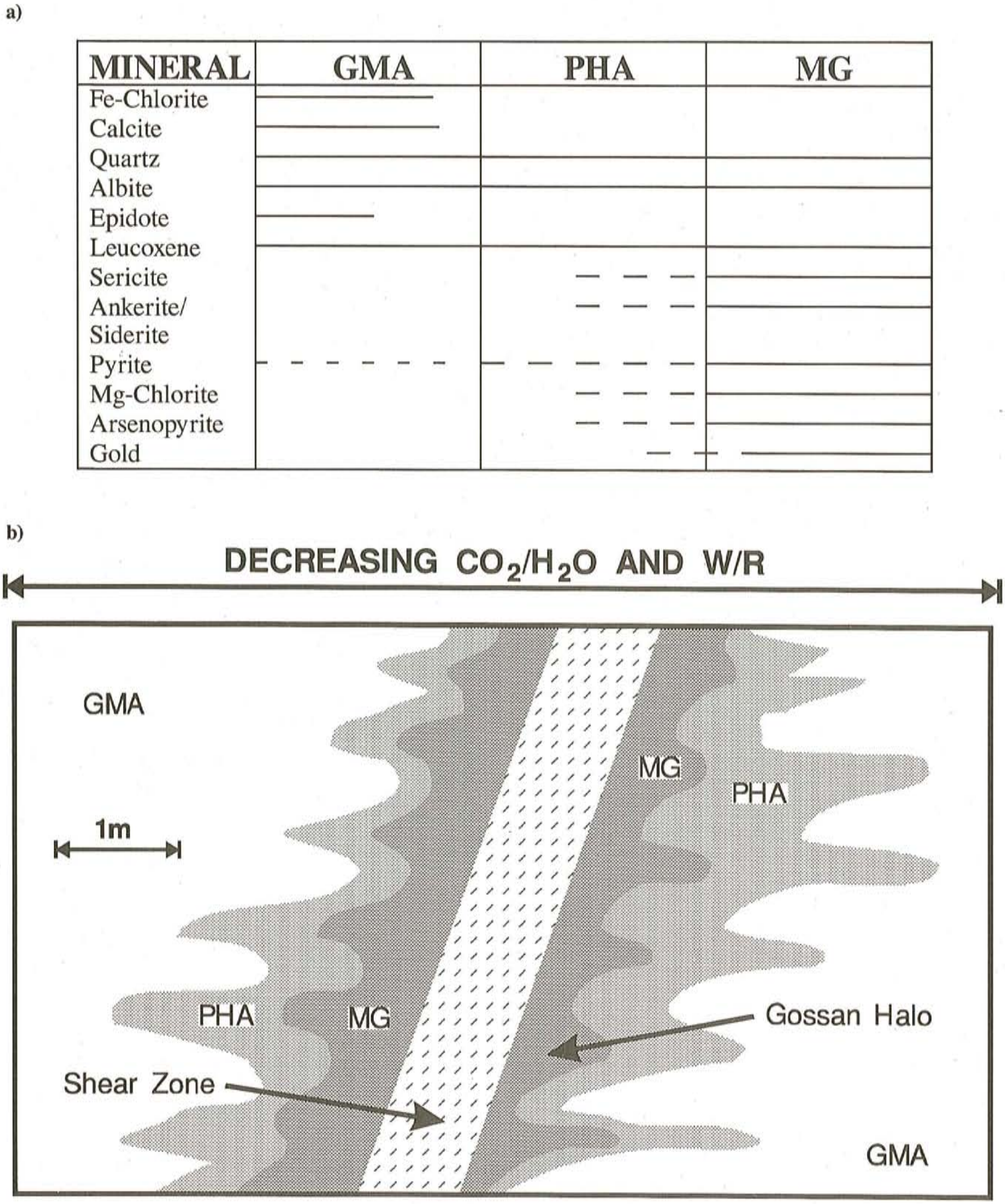


Figure 4. *(a) Mineral paragenesis of select mineral phases for alteration zonations in gabbro. Stable phases (———), added metastable phases (— — — and - - - - - -). (b) Schematic block model of the alteration zonation showing spatial relationships of the GMA-, PHA-, and MG-Zones to Riedel shear as well as decreasing CO_2/H_2O and W/R ratios away from shear zone.*

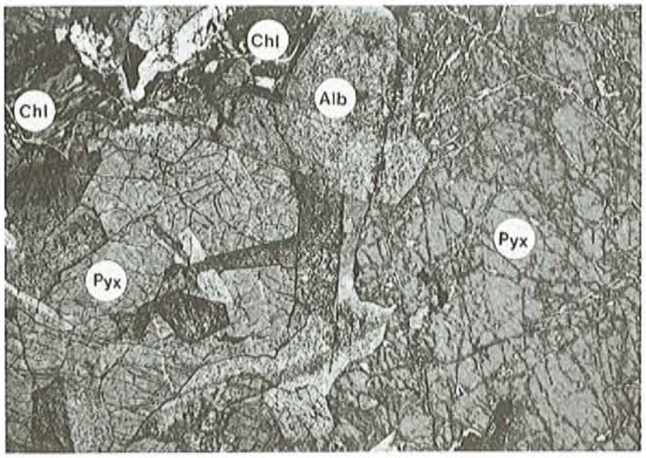


Plate 8. *Photomicrograph of fresh gabbro from the GMA-Zone showing fresh pyroxenes (Pyx), albitized plagioclase (Alb), and minor chlorite phases (Chl). (Field of view approximately 6 mm.)*

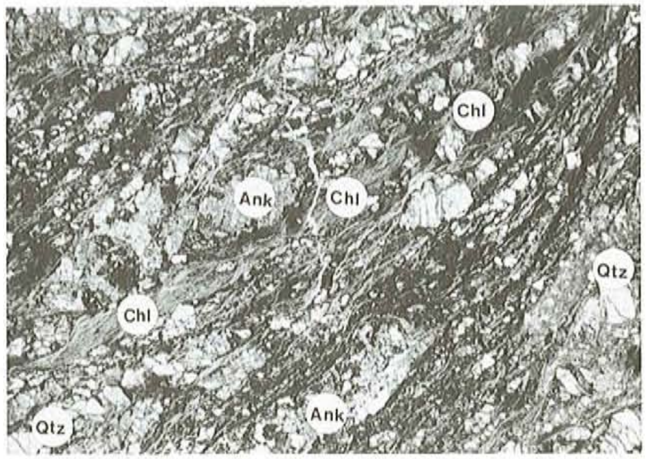


Plate 9. *Photomicrograph of intensely altered and sheared gabbro from PHA-Zone. Note the abundant penninite (Chl), ankerite (Ank), and minor quartz (Qtz) developed in shear bands. (Field of view approximately 6 mm.)*

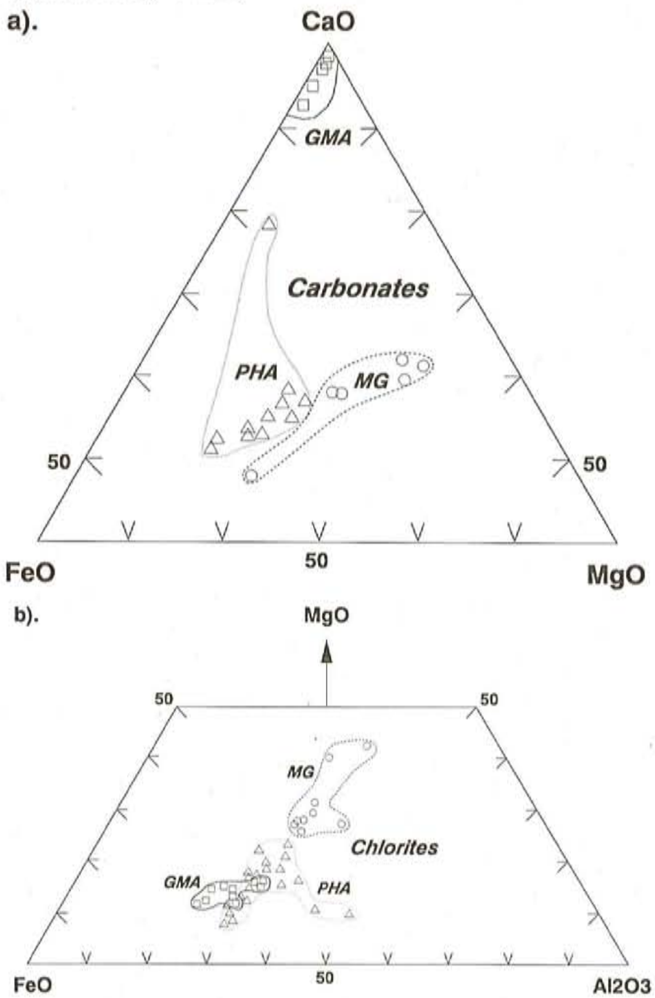


Figure 5. *Semi-quantitative SEM data for carbonate and chlorite phases from different lithological domains: GMA-Zone (squares), PHA-Zone (triangles), and MG-Zone (circles). (a) Carbonate data showing changing chemistry from Ca to Mg, Fe-rich varieties with progressive alteration. (b) Chlorite data showing increasing Mg-chemistry with alteration.*

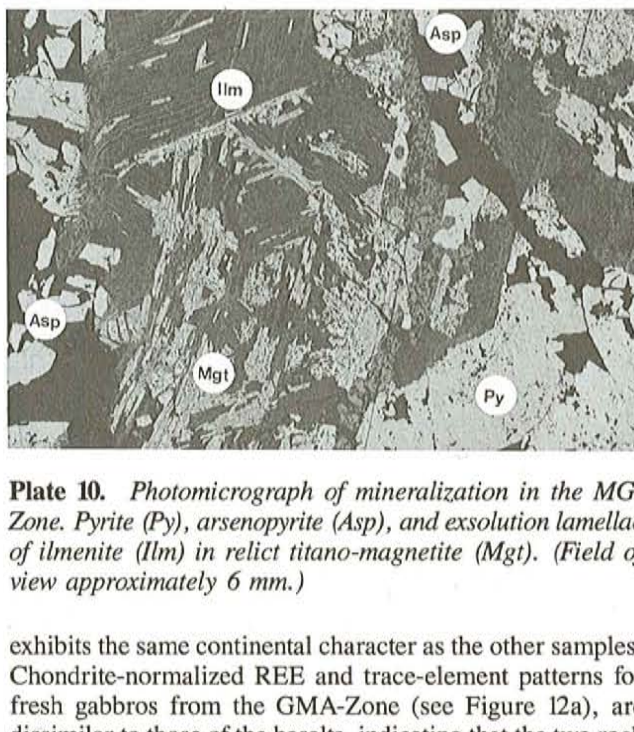


Plate 10. *Photomicrograph of mineralization in the MG-Zone. Pyrite (Py), arsenopyrite (Asp), and exsolution lamellae of ilmenite (Ilm) in relict titano-magnetite (Mgt). (Field of view approximately 6 mm.)*

exhibits the same continental character as the other samples. Chondrite-normalized REE and trace-element patterns for fresh gabbros from the GMA-Zone (see Figure 12a), are dissimilar to those of the basalts, indicating that the two rock types are probably not genetically related. (The LREE and HREE content in the basalts are at most 12 times as great as that of the gabbro.) Based on this criteria, as well as the intrusive relationships observed between basalts intruded by gabbro, it is apparent that the volcanic rocks represent an earlier magmatic episode unrelated to the gabbros.

MAFIC DYKES AND SILLS

The hydrothermal alteration progression has a well-defined geochemical signature. Plots of Sb, As, and Au versus S (Figure 8) illustrate the bulk changes in chalcophile metal chemistry with progressive alteration. Three groupings can be identified for each plot corresponding to the GMA-, PHA-

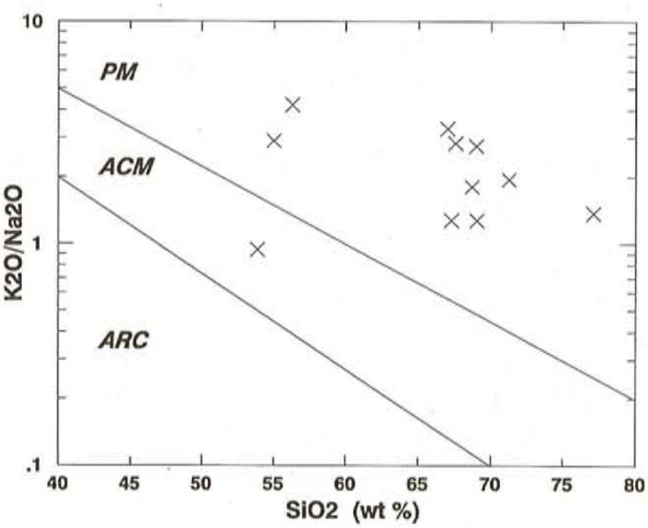


Figure 6. *Tectonic discrimination diagram for sedimentary rocks. PM=passive margin, ACM=active continental margin, ARC=island arc. Fields from Roser and Korsch (1986).*

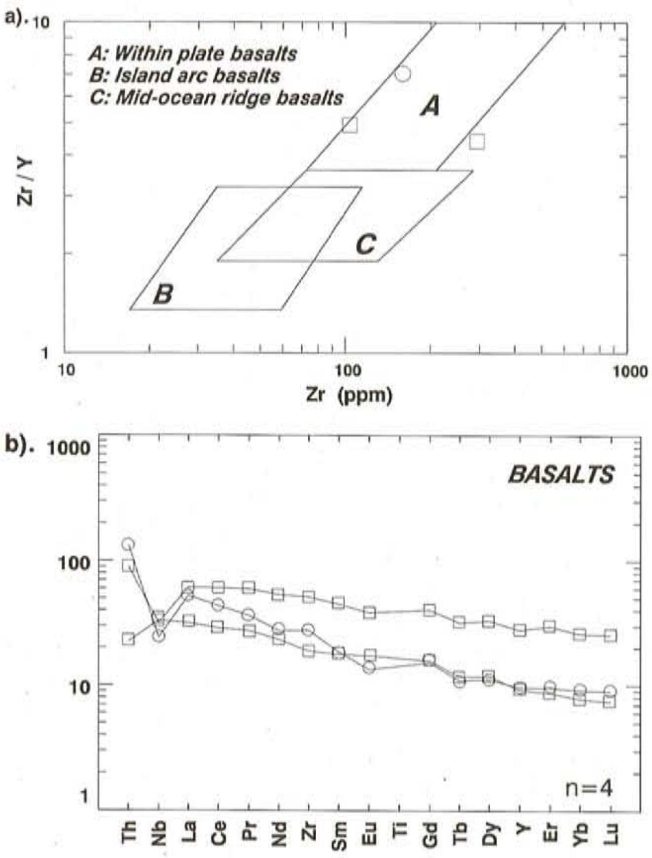


Figure 7. *Trace- and rare-earth-element plots for volcanic rocks. (a) Tectonic discrimination diagram from Pearce and Norry (1979) suggesting a within-plate setting for basalts. Basalt samples from Duder Lake (squares) and Dan's Pond 20 km southwest of Duder Lake (circle). (b) Chondrite-normalized rare-earth and trace-element pattern showing typical continental signature with LREE enrichment and HREE depletion. Symbols as per Figure 7a.*

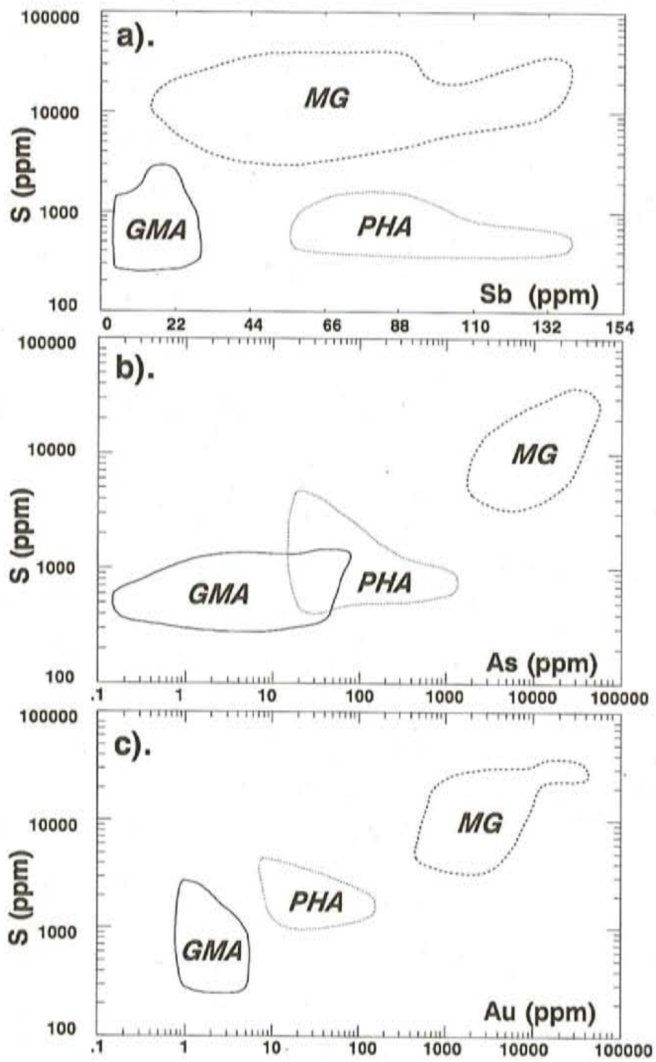


Figure 8. *Plots characterizing the nature of alteration and mineralization. (a) S vs. Sb. (b) S vs. As. (c) S vs. Au. Abbreviations for fields same as those used in text.*

and MG-Zones, which exhibit increases in As and Au with increasing S content. The Sb plot may indicate greater mobility of Sb relative to S, in which Sb was remobilized from the MG-Zone to the PHA-Zone without any appreciable S mobilization. The As and Au plots show a continuum between non-mineralized and mineralized rocks having a noticeable positive slope. In all instances, rocks of the PHA-Zone occupy an intermediate position.

The alteration progression can be further characterized on the basis of CaO and CO_2 contents representative of the pervasive carbonatization. The plot of CO_2 versus CO_2/CaO depicts increase in ferromagnesian carbonate chemistry with increasing alteration (Figure 9). Samples from the GMA-Zone that underwent regional metamorphic alteration, plot in a defined field representative of a calcite chemistry. Rocks exhibiting intense hydrothermal alteration, plot in fields dominated by ankerite and ferroan dolomite chemistry. Rocks that exhibit hydrothermal alteration effects, and having an

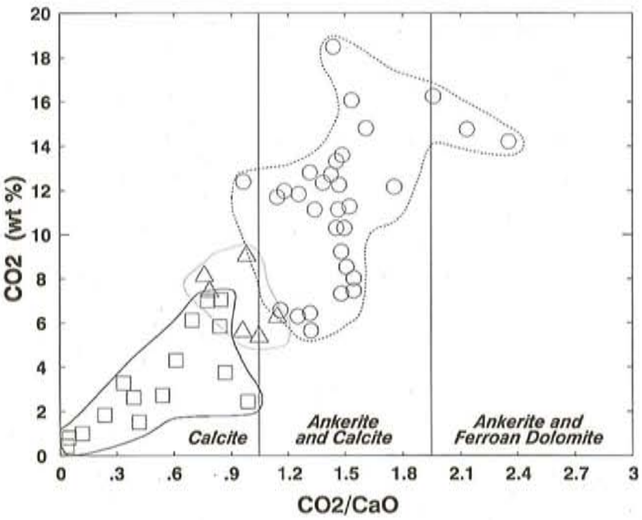


Figure 9. *Carbonate classification using CO_2 vs. CO_2/CaO (Modified from Dubé, 1985). Symbols as per Figure 5.*

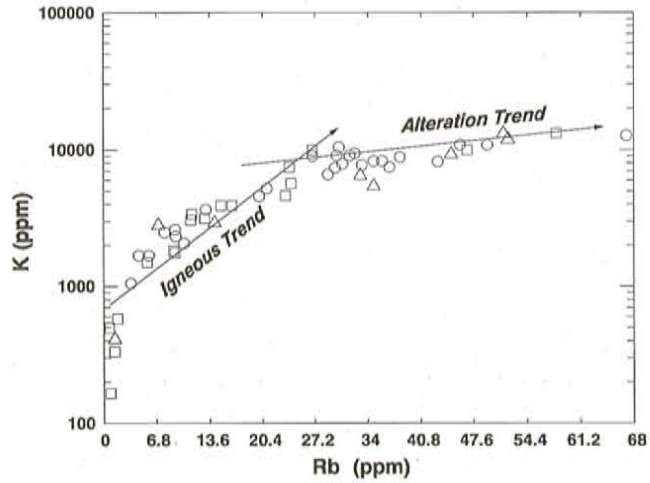


Figure 10. *Plot of K vs. Rb exhibiting data trends representative of igneous and alteration trends. Symbols as per Figure 5.*

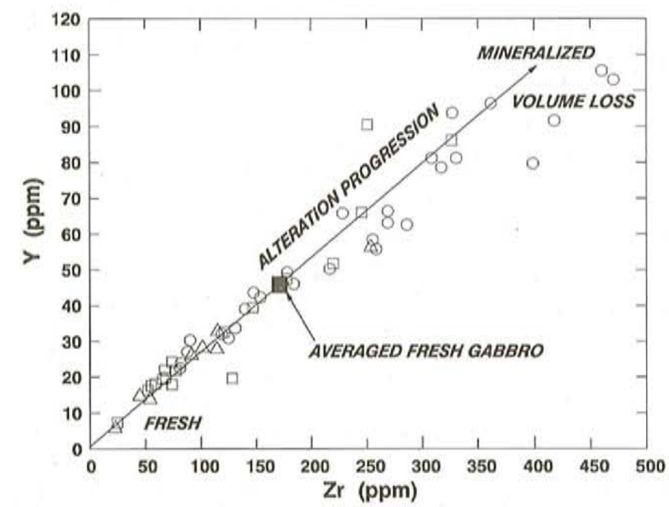


Figure 11. *Plot of Y vs. Zr illustrating alteration progression and volume loss in relation to 'averaged fresh gabbro'. Symbols as per Figure 5.*

intermediate gold content, plot in fields overlapping the two end-members, thus containing both calcite and ankerite. The increases in CaO and CO_2 suggest that the mineralizing fluid was probably rich in CO_2. This inference is further supported by preliminary fluid inclusion studies, which have found that ore-stage (primary) fluid inclusions have a substantial CO_2 vapour component.

Trace-element-geochemical data also exhibit the changing chemistry due to hydrothermal alteration. The plot of K versus Rb exhibits two dominant trends: an igneous trend and an alteration trend (Figure 10). Although there is some overlap between the different gabbro types, the igneous trend on a whole comprises those samples occupying the GMA- and PHA-Zones. Some MG-Zone samples plot along this trend, reflecting the alteration mineralogy. The alteration trend, defined by increasing Rb and minor addition of K is dominated by samples from both the PHA- and MG-Zones suggesting that the Rb increase may be attributable to volume loss upon albitization. Hydrothermal alteration of the plagioclase-forming albite may cause mobility of Rb in the plagioclase, thus causing volume reduction and apparent Rb enrichment. The excess Rb is then incorporated into newly forming sericite phases prevalent to more intensely altered gabbros.

Plots of immobile elements such as Y versus Zr (Figure 11) also show this alteration progression. Although the data show a well-defined positive trend from low abundance GMA-Zone samples to higher abundance MG-Zone samples, the increase is probably a reflection of volume loss during alteration. As a point of reference, the average fresh gabbro concentration is plotted as well.

The chondrite-normalized plots (Figure 12) illustrate definable changes in zonal geochemistry. The GMA-Zone samples show approximately 10 X enrichment and a pattern, which is rather flat, suggesting no appreciable change in trace and REE chemistry relative to chondrite (Figure 12a). Samples from the PHA-Zone exhibit increased concentrations of approximately 20 X, inferring some addition and/or concentration due to volume loss of REE's during alteration (Figure 12b). The pattern also shows slight enrichment in the LREE's relative to the HREE's suggesting that a newly forming, hydrothermally produced mineral phase, such as sericite, preferentially incorporated the LREE's. The HREE's, however, maintain the same flat pattern implying no substantial enrichment.

The most dramatic changes observed in REE chemistry are exhibited by those samples from the MG-Zone (Figure 12c). Relative to chondrite, these samples are enriched up to 50 X and once again show similar REE behaviour as PHA-Zone samples. The LREE enrichment is most likely

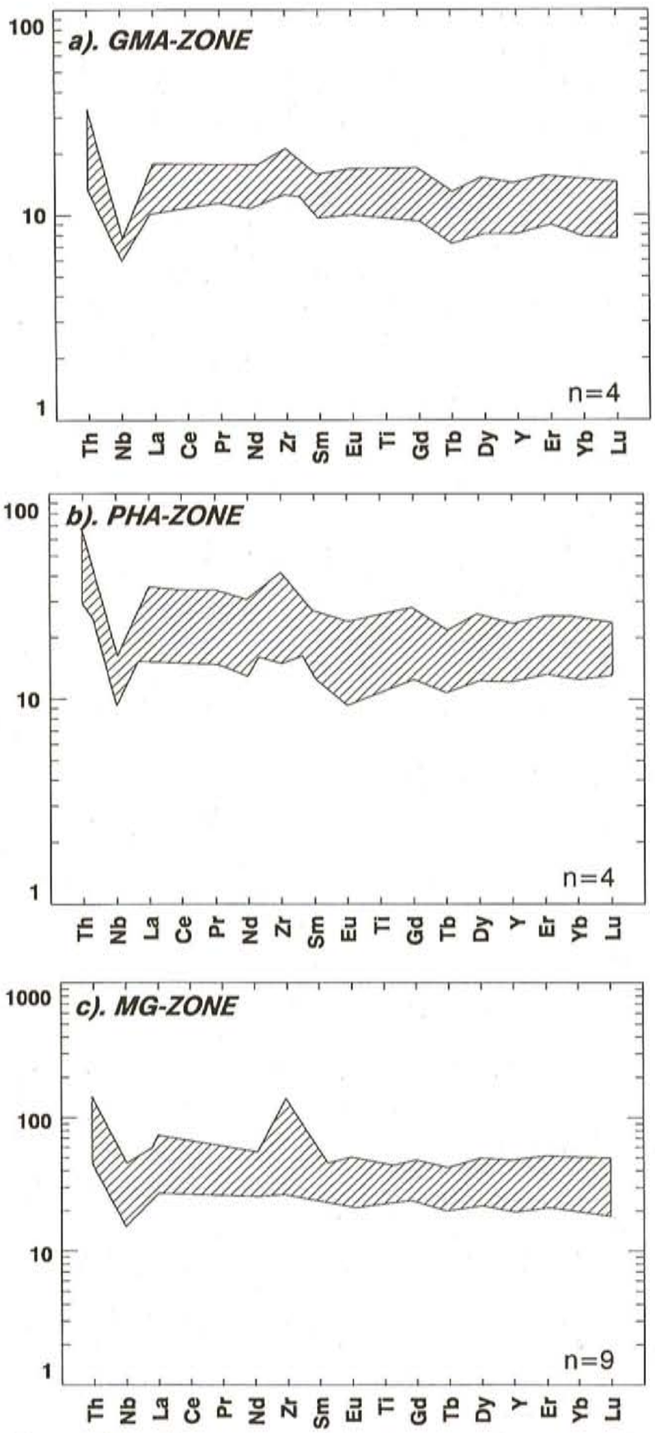


Figure 12. *Chondrite-normalized rare-earth and trace-element plots for samples representative of the three different gabbro types. (a) GMA-Zone. (b) PHA-Zone. (c) MG-Zone. Note the relative enrichments as well as slight LREE enrichment relative to the HREE concentrations. (Norm values from Taylor and McLennan, 1985.)*

attributable to the addition of sericite, which is most prevalent to the MG-Zone. Although concentration increases with progressive alteration, no addition is observed in the HREE's, perhaps suggesting that the bulk of the enrichment may be attributable to volume loss resulting in a relative enrichment. The enrichment in the LREE's would also be strongly dictated by volume loss, but due to the changing shape of the pattern it infers that some LREE addition has taken place.

To summarize, the geochemistry of the gabbros suggests volume loss during progressive alteration with contemporaneous addition of CaO, CO_2, Au, As, Sb and minor LREE addition. The increases in concentration of these elements and/or oxides are a direct result of increased intensity and longevity of the hydrothermal alteration. The ore fluids are inferred to have contained abundant CO_2, Au, As as well as LREE's complexed with Cl-complexes.

SUMMARY, DISCUSSION AND MODEL

Two northeasterly trending sedimentary and volcanic units of Ordovician to Silurian age outcrop in the Duder Lake area. Silurian, subaerial red beds of the Wigwam Formation of the Botwood Group are in fault contact with Ordovician–Silurian turbiditic sandstones and siltstones of the Davidsville Group. Although the contact is faulted, field observations suggest that the units may have been conformable. A volcanic unit inferred to be the equivalent of the Lawrenceton Formation of the Botwood Group is found to be in fault contact with the lower part of the Wigwam Formation.

Intruding all rock units are gabbroic to dioritic sills and dykes of inferred Siluro-Devonian age—some of which contain epigenetic gold mineralization.

Gold mineralization is developed in gabbroic and graphitic sedimentary rocks that are shear-controlled. Gabbro- and sedimentary-hosted mineralization can be further subdivided on the basis of inherent features. Gabbro-hosted mineralization can be subdivided into groups:

1) shear-controlled disseminated sulphide wall-rock replacement (e.g., Corvette and Stinger), and

2) shear-controlled quartz–carbonate veins containing patchy sulphides and gold (e.g., Flirt).

The sedimentary-hosted mineralization (*viz.* Stinger) has a mode of occurrence similar to Flirt (shear-controlled, vein-hosted with patchy sulphides and gold).

Hydrothermal alteration of the gabbros is found superimposed on low-angle Riedel shears that appear to be third-order structures related to the Dog Bay Line. Proximal to the shears, alteration is most intense and locally contains elevated gold values in excess of 30 000 ppb from grab samples. Away from the shears, alteration intensity gradually diminishes to 'fresh' gabbro that preserves low- to mid-greenschist-facies metamorphic assemblages. It appears that higher order structures had higher fluid to rock interaction than the primary structures, since gold mineralization and the intense hydrothermal alteration are found proximal to them. This suggests that Flirt was located at the periphery of the hydrothermal system because it did not have the same intensity of alteration as did the other gabbro-hosted showings.

Stinger shows similar alteration systematics but is vein-hosted having hydrothermal alteration assemblages confined to narrow envelopes along the veins.

Alteration studies by Dubé (1985) and Dubé *et al.* (1987), on the Bourbeau Sill and associated gold mineralization in northern Quebec, documented a style of alteration similar to that observed at the Goldstash and Corvette prospects, Duder Lake. These authors attributed mineralogical changes in the hydrothermal zone to changing CO_2/H_2O and W/R (water/rock) ratios outwards and away from the shear zone that acted as the fluid conduit (Figure 4). A similar scenario can be inferred for alteration at the Duder Lake gold showings where CO_2/H_2O and W/R were highest closest to the Riedel shears and lowest away from them.

Definition of the gold phases is problematic because visible gold cannot be observed, even in thin-section. Assay values in excess of 30 000 ppb Au have been obtained from grab samples that contain abundant disseminated Fe-, As- and Sb-rich sulphides (up to 20 percent modal). Such phenomenon is quite common in hydrothermal gold occurrences, which contain finely disseminated pyrite and arsenopyrite (Springer, 1983). Cook and Chryssoulis (1990) found that Au can replace the excess As that occupies Fe-sites in As-rich varieties of arsenopyrite. A similar mode of Au gold occurrence is envisaged for gold mineralization at Duder Lake.

Geochemistry of sedimentary and volcanic rocks suggests a passive margin and within-plate tectonic settings respectively, reaffirming regional tectonic interpretations. Comparison of the volcanic rock and gabbro REE plots suggests that the two are not genetically related (i.e., they are derived from different magmatic episodes).

The geochemistry of fresh, altered, and mineralized rocks exhibits change with hydrothermal alteration. CO_2, CaO, As, Au, S, and Au all show marked increases with increasing alteration intensity. Volume losses accompanying hydrothermal alteration can also be observed in the data. Potassium, Rb, Y, and Zr exhibit increases even though they were probably not added by the hydrothermal fluids. The increases observed are a result of volume loss and/or element remobilization due to the breakdown of pre-existing mineral phases (e.g., Rb derived from albitization of plagioclase). Both LREE's and HREE's show similar volume loss effects. Although some LREE's appear to be added during intense alteration, most of the REE increases are due to concentration via volume loss.

Evidence for Gander Zone basement involvement can be inferred from lithophile elements that exhibit a geochemical signature indicative of fluid composition (e.g., Kerrich, 1988). A plot of K percent versus Rb can infer a likely fluid source region and as shown on Figure 13 all samples plot along a trend clustered about the K/Rb=200 line named the Main Trend (MT) by Kerrich (1988). The MT field is indicative of fluids derived from an average crustal source (*viz.* metamorphism of typical average crustal rocks such as Gander Zone basement). The other two fields (i.e., oceanic and pegmatitic-hydrothermal) have ratios too high and too low, respectively. Because there is a good data fit with the MT field for samples from Duder Lake, it is inferred that it is the likely fluid source region.

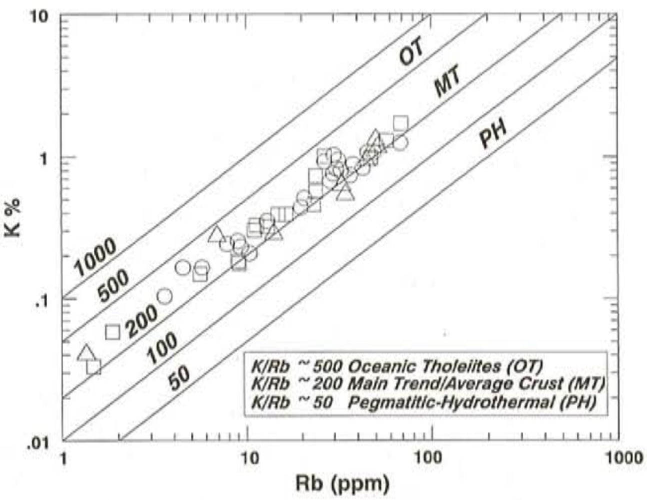
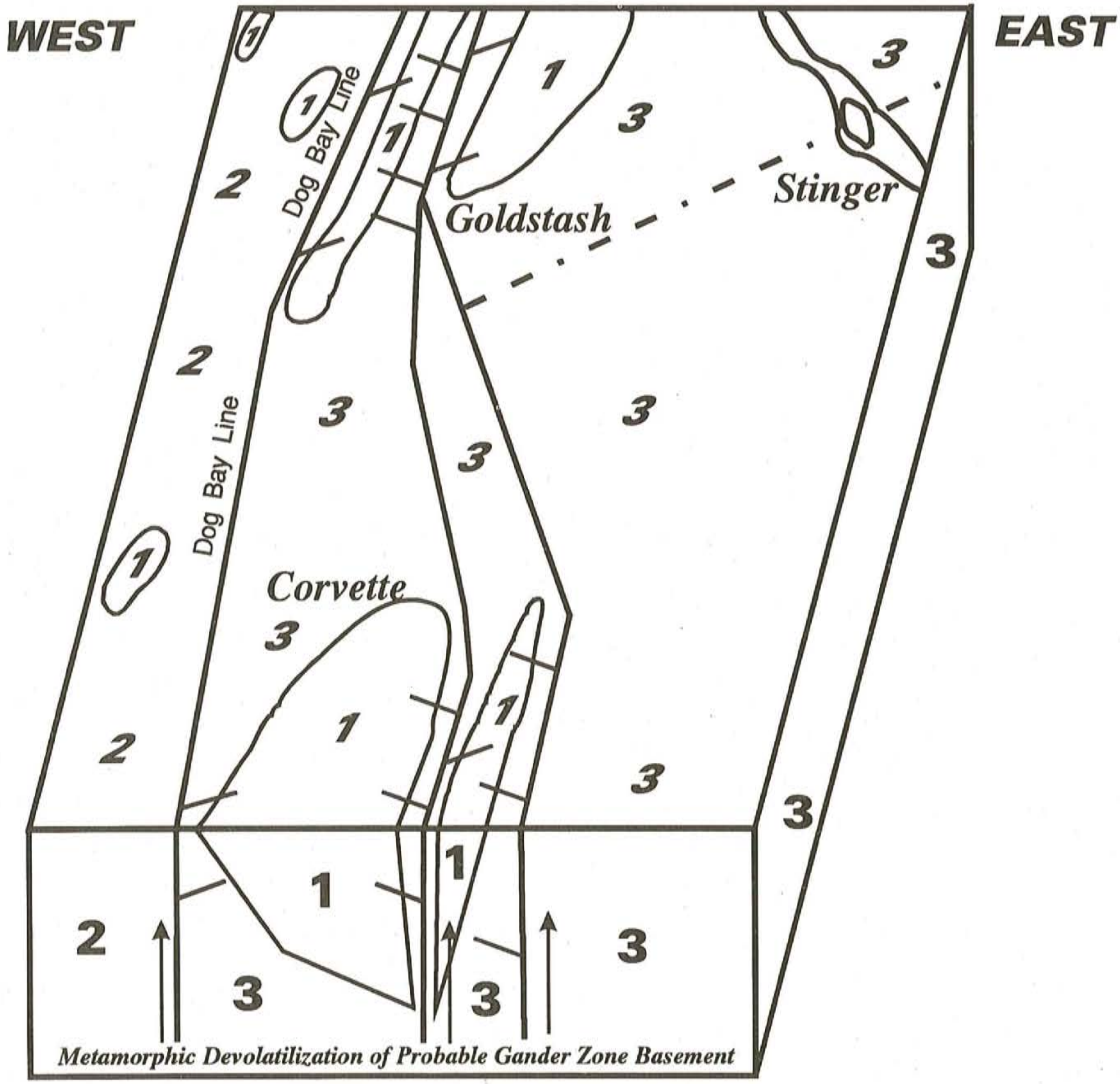


Figure 13. *Plot of K percent vs. Rb (ppm) illustrating likely fluid source reservoirs. Symbols as per Figure 5. (Modified from Kerrich, 1988.)*

Based on geochemical, geological, and structural relationships, a simplistic model for gold mineralization can be inferred for the Duder Lake gold showings (Figure 14). During the Late Ordovician to Early Silurian, siliciclastic rocks were deposited on continental margins and/or fault-bounded basins with contemporaneous subaerial volcanism (Davidsville and Botwood groups respectively). Both units were deformed and metamorphosed to low- to mid-greenschist facies during the Silurian, which also either activated or reactivated the Dog Bay Line. Continued orogenesis caused partial melting in the lower crust and melts ascended to upper crustal levels via the permeable fault zones still active at the time. Metamorphism of probable Gander Zone basement rocks produced fluids enriched in CO_2 as well as Sb, As, and Au, which were focussed up along these regional shear systems. The huge volumes of rock that were 'stripped' of these elements allowed for sufficiently high concentrations of Au to be partitioned into the fluid phase.

Fluids percolated through the fault zones until disequilibrium occurred, usually when Fe-rich gabbros or graphitic sedimentary rocks were encountered. This allowed for precipitation of Au in conjunction with sulphide phases such as pyrite and arsenopyrite (Barley and Groves, 1990). Precipitation of Au and sulphides correlated with the most intense hydrothermal alteration proximal to Riedel shears.



1 *Siluro-Devonian gabbros and diorites*
2 *Silurian subaerial red beds (Wigwam Formation, Botwood Group)*
3 *Ordo-Silurian turbidites (Davidsville Group)*

Low angle Riedel shears (2nd and 3rd order structures)

Faults (defined, inferred)

CO_2-rich fluids containing Au, As, Sb derived from metamorphic devolatilization of probable Gander Zone basement. Permeates all orders of structures but concentrated in Riedel shears

VERTICAL SCALE: Approx. 1000 m
HORIZONTAL SCALE: Approx. 2000 m

Figure 14. *Schematic model for gold mineralization at Duder Lake.*

The model may be valid for similar deposits elsewhere in the eastern Dunnage Zone. More fluid inclusion and isotopic work will delineate the mechanisms inherent to mesothermal-like gold mineralization at Duder Lake.

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