

Geochemical profile of a carbonate-quartz alteration zone in footwall rocks of the Stirling VMS base metal deposit, Richmond County, Cape Breton Island

D. J. Kontak

Introduction

The Stirling massive sulphide deposit, located in southeast Cape Breton Island (Fig. 1), is a Zn-rich base metal deposit hosted by volcanoclastic rocks of the 680 Ma Stirling Group. Although initially discovered as a copper prospect in the 1890s, it was developed in the 1930s and 1950s as an underground massive sulphide mine with production of about 1.2 million tonnes of 6.4% Zn, 1.5% Pb, 0.74% Cu and 2.2 oz./t Ag and 0.03 oz./t Au (Miller, 1979). Since production ceased, exploration on the property and adjoining areas has continued intermittently over the past 40 years.

Because of the lateral continuity of the sulphide deposit, its location within a shear zone, and the appearance of replacement textures, the deposit was originally considered to have formed as a result of magmatic-related solutions ascending a shear or fault zone and replacing the host rock sequence (Alcock, 1930; Weeks, 1924, 1954; Watson, 1954, 1957). The base metal mineralization was re-interpreted as being related to exhalative processes in the 1970s (Poole, 1974; Miller, 1979) based on analogies with younger, less deformed massive sulphide deposits (e.g. Kuroko deposits of Japan) and new theories proposed for similar mineralization (see Franklin *et al.*, 1981, for review). However, an important aspect of the competing genetic models proposed for the Stirling deposit is interpretation of the origin of a quartz-talc-carbonate (QTC) rock that is intimately associated with mineralized zones throughout the deposit (Kontak, 1998). Originally considered to be an alteration halo in the epigenetic, vein model of early workers, Miller (1979) was the first to formally propose this lithology as an exhalative horizon and syngenetic with respect to the sulphide mineralization. However, whereas Miller interpreted the QTC rock to have formed as a result of exhalative processes on the ocean floor, recently Kontak (1998, 1999) suggested that most of this rock formed as a replacement of volcanoclastic rock beneath the sediment - ocean floor interface. More recently Kontak (1999) has suggested the QTC was deposited from low-temperature fluids (i.e. ca. 80-100°C)

temporally and spatially related to the same geothermal system that generated the higher temperature (i.e. ca. 300°C), sulphide-depositing fluids.

Whereas generation of the low-temperature hydrothermal system is considered analogous to modern travertine deposits (e.g. Yellowstone Park, Wyoming), the high-temperature hydrothermal system is analogous to black smokers at modern vent sites on the ocean floor. The Stirling deposit is not unique in terms of the association of quartz-carbonate alteration with massive sulphide mineralization, as large sulphide deposits (i.e. several million tonnes) with somewhat similar association occur in the Proterozoic of the Sudbury area (e.g. Errington and Vermillion Zn-Cu-Pb deposits) and Bergslagen district of Sweden (Garpenberg deposit) (see Rousell *et al.*, 1997). Documentation of the nature, genesis and role of the QTC alteration is key to the understanding of the Stirling massive sulphide deposit.

The case for a replacement origin for QTC rock is based on results of logging drill core stored at the NSDNR Core Library in Stellarton, petrographic examination of these materials, and subsequent geochemical assays of drill core samples.

Geology of the Stirling Deposit Area

The Stirling deposit is located within the ca. 680 Ma Stirling Group, a sequence of mafic and felsic volcanic and volcanoclastic rocks of epiclastic origin interbedded with lenses of fine- to coarse-grained clastics composed of detritus derived from the volcanic rocks (Barr *et al.*, 1996). The Stirling Group was interpreted by Macdonald and Barr (1993) to have been deposited within and around a trough flanked by volcanic centres in an intra-arc setting of continental affinity. Relevant with respect to massive sulphide mineralization are observations that sedimentary structures (i.e. rip-up clasts, graded bedding, basal scours) within the sequence indicate subaqueous mass transport with deposition below

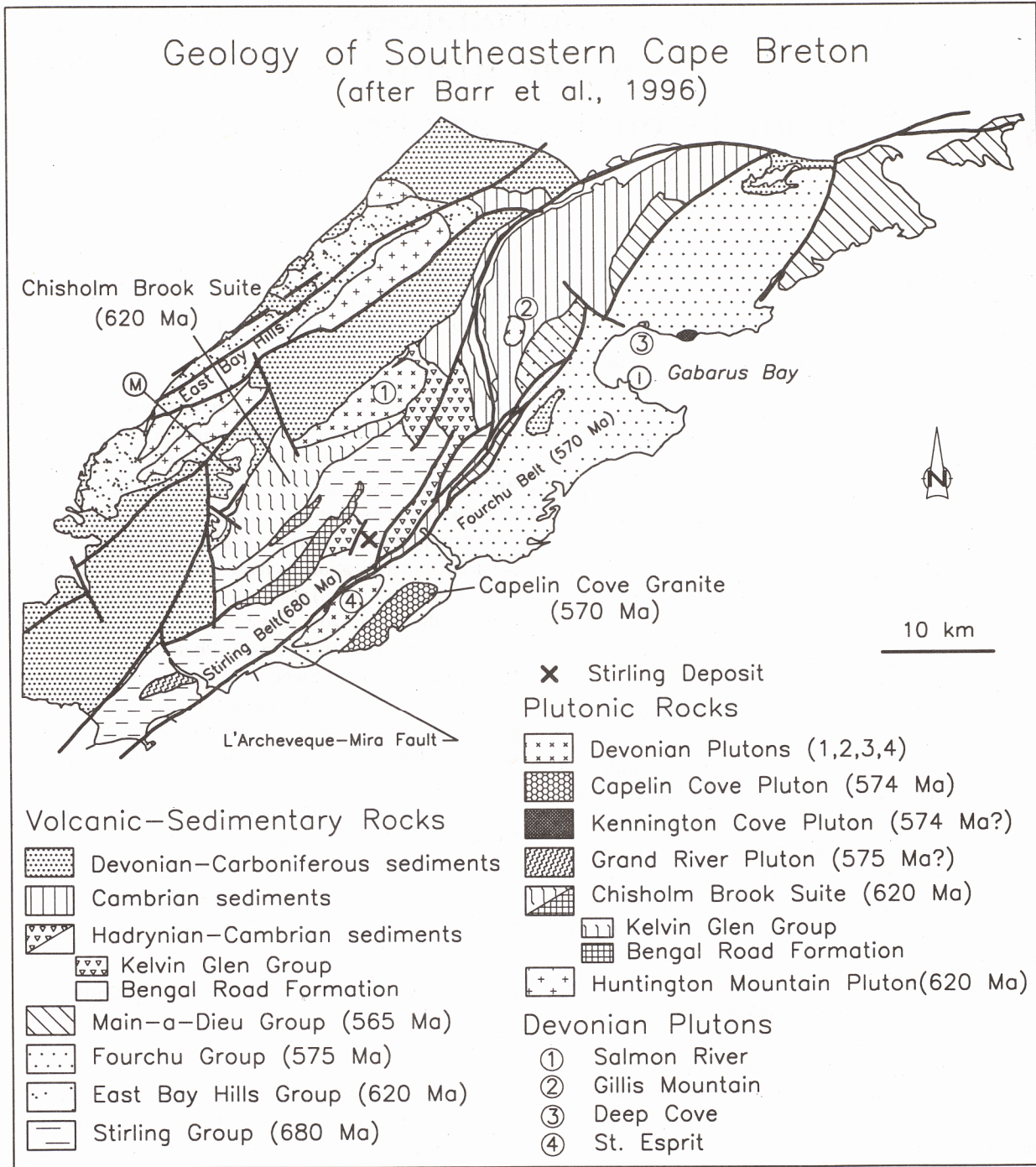


Figure 1. Regional geological map of southeast Cape Breton Island showing the distribution of Late Hadrynian volcanic-sedimentary packages and intrusive rocks with younger overlapping sequences and plutonic rocks. Location of the Stirling Zn-Pb-Cu-Ag-Au deposit is indicated within the 680 Ma Stirling Group rocks.

wave base (Macdonald and Barr, 1993; Kontak, 1998, and herein). Although the felsic and mafic volcanic rocks show little evidence of subaqueous deposition, the interbedded sedimentary rocks provide evidence of such a setting.

Structurally, the Stirling Group is variably deformed, with northwest-southeast directed compression and northeast strike-slip movement, demonstrated by the highly strained, mylonitic zones that grade into less deformed areas over distances of tens of metres. The

most intense deformation on a regional scale occurs proximal to the Mira-L'Archeveque Fault (Fig. 1); however, highly strained rocks also occur throughout the deposit area and are very common in drill core from the deposit. The presence of deformation is a hindrance to study of the QTC rock since this unit has preferentially taken up a lot of the strain in the deposit area and most primary textures have been destroyed.

The Stirling Group is intruded by and bounded to the north by the 620 Ma Chisholm Brook plutonic suite, but this intrusive complex has not affected rocks at the Stirling deposit. Near the deposit area Stirling Group rocks are overlain unconformably by coarse clastics of Late Hadrynian age (Fig. 1).

Deposit Geology

The geology of the Stirling deposit and surrounding area (Fig. 2) consists of a variety of volcanoclastic rocks, mafic and intermediate flows, and felsic units, both extrusive and intrusive (i.e. domes or subvolcanic intrusions), that are intruded by mafic sheets and dykes. A large gabbroic body lies just south of the deposit, and is the source of the numerous mafic dykes that cut the ore zone (Watson, 1957). Many previous workers have noted that the stratigraphy youngs to the northwest and that rocks beneath the deposit area are dominantly felsic (the rhyolite porphyry unit in Fig. 2), whereas along strike and stratigraphically overlying the deposit intermediate volcanic and sedimentary rocks dominate with rare occurrences of felsic rocks. In addition, the stratigraphy thickens to the northeast and down-dip of the deposit, which suggests that the depositional basin may have thickened to the northeast.

Based on logging of drill core, the stratigraphy immediately beneath the ore zones is dominated by fine- to medium-grained, dark green to dark grey volcanoclastics commonly displaying graded beds of cm to m thickness. These rocks are cut at depth by rhyolite porphyry. This simple stratigraphy is complicated by: (1) stratigraphic facing directions to the east in the upper part of hole KA2 (Fig. 3), as indicated by graded bedding, which suggest that a fold closure may exist; and (2) interference patterns (Type 1) present in drill core reflect overprinting of earlier folds (F_1) by second generation (F_2) folds. Thus, it is likely that isoclinal folds are present. Further complicating interpretation of the geology are the following: (1) lateral facies changes, (2) uncertainty of whether felsic and volcanic units are flows, sills or subvolcanic plugs, and (3) presence of a variety of alteration types (carbonate, silica, sericite, epidote).

Of particular relevance to this work is the extent of a large felsic centre extending beneath the ore zones which is interpreted to be subvolcanic in origin based on the dominantly massive nature of the rock, mutual cross-cutting relationships of felsic porphyry with other felsic dyke rocks, and cross-cutting relationships with the volcanoclastic rocks observed in drill core. This unit may be similar to the subvolcanic sills and porphyries that underlie many massive sulphide deposits, as discussed by Galley (1996), and an integral part of current models for massive sulphide deposit formation (Franklin, 1993). These intrusions provided the energy for circulating hydrothermal fluids which caused leaching and alteration in an extensive zone above the subvolcanic intrusion.

Alteration Profile

In order to examine the nature of the QTC rock, cores from several drillholes were logged; representative drill-hole sections are illustrated in Figure 3. These drillhole logs together define an oblique longitudinal section. A core section of altered volcanoclastic rock from diamond-drill hole KA-2 (Fig. 4) was sampled in detail for lithochemistry.

In drill core one observes the generally monotonous, banded and graded, dark green-grey volcanoclastic unit as footwall rock beneath the massive sulphide zone, although near the mineralized zone the rocks are distinctly finer grained and layering is on a mm to cm scale (versus cm to m scale farther beneath the sulphide zone). A well developed fabric is present and is usually 30-40° to the core axis, but in places the fabric is parallel to the core axis, which presumably relates to folding (Fig. 3). As previously noted, interference patterns are common in drill core, particularly in QTC rock, and where intensely deformed the rock has a schistose fabric. The volcanoclastic unit becomes variably altered to a fine-grained, massive to banded, white to whitish-grey rock where dominated by quartz and carbonate, and pale buff where talc is present (Figs. 4, 5). In some sections the rock is mottled, with up to 60-80% alteration, whereas in other places the core is 100% QTC rock.

In thin section, the volcanoclastic rocks are seen to comprise variable mixtures of anhedral quartz, altered volcanic clasts with layering, carbonate, chlorite and fine-grained white mica. The QTC lithology is variable in nature with the following types present: (1) very fine-grained, massive silica-rich rock (with or without patches of coarse quartz) characterized by subgrain development and radial habit, (2) fine-grained, layered carbonate and quartz rock, and (3) carbonate rock with patches of colloform and/or radially-textured material.

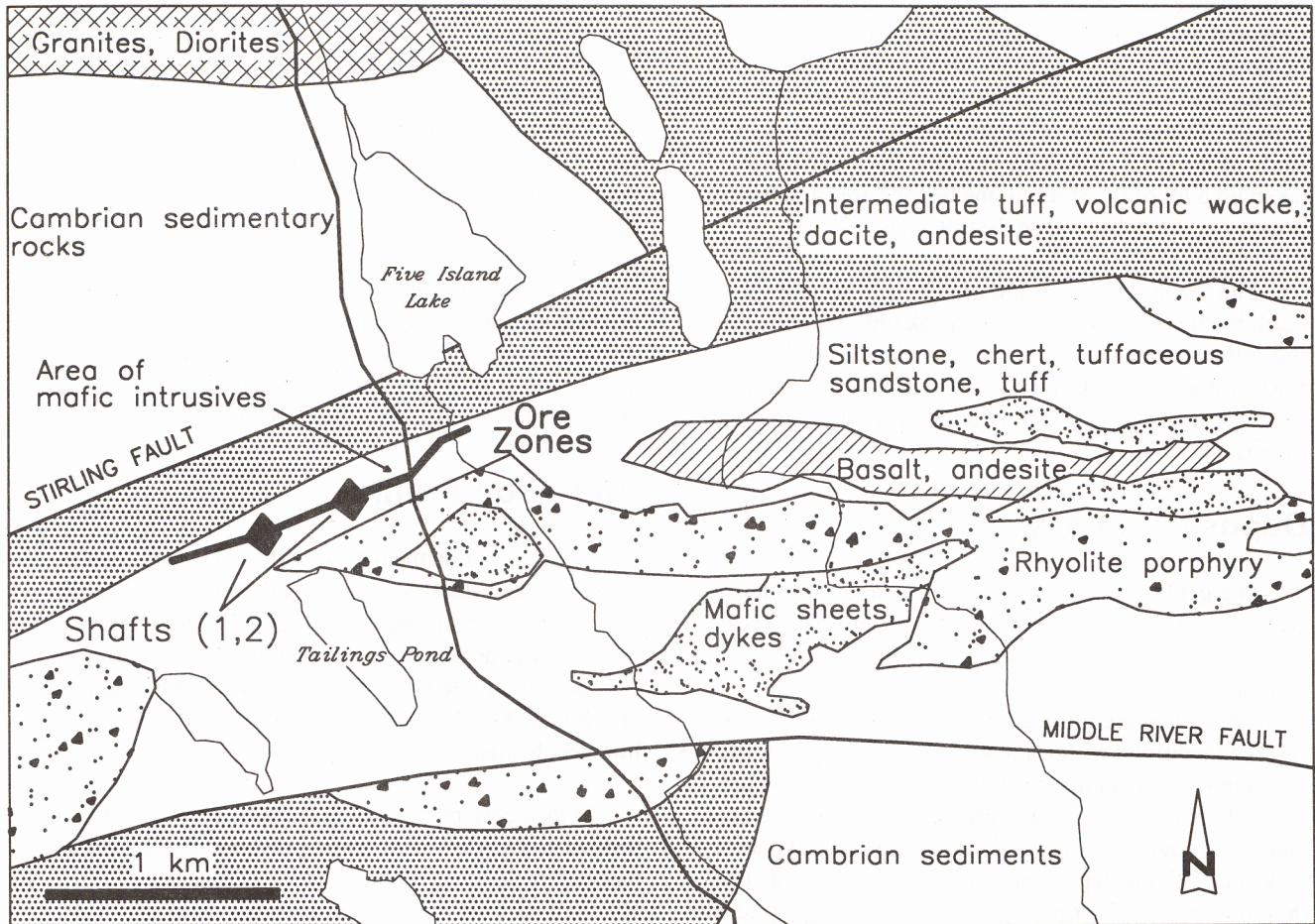


Figure 2. Geological map of the Stirling area (modified after Macdonald, 1989) showing distribution of the main rock types, projection of the ore zones, location of the two shafts (#1 and #2) that accessed the deposit and the tailings pond.

The amount of deformation varies, with the latter samples obviously free of strain since delicate textures are preserved. Where sulphide is present (i.e. pyrite), the silica-carbonate material (type 2, above) is paragenetically later.

A 60 foot section of core from diamond-drill hole KA-2 illustrates well the typical nature of the QTC alteration (Fig. 4). Of particular note in this section are the following observations. (1) Dark green to black, fine-grained volcanoclastic rock is variably bleached to shades of grey and eventually the rock is completely converted to a whitish quartz-carbonate rock with no vestiges of the precursor. (2) In the partially altered section, a remnant fabric is present (also see Fig. 5) which may represent primary layering observed in the unaltered rock or a layer-parallel fabric. In at least some cases the tectonic fabric and what is probably primary banding in

quartz-carbonate rock (inherited) are parallel. If this layering is primary, then this is an important observation as it indicates that the alteration was a constant volume phenomenon which resulted in preservation of textures. (3) Thicknesses of the alteration zones are variable. For example, of the altered zones in Figure 4, the apparent thicknesses are ca. 8 feet, 3 feet and 16 feet. (4) The nature of quartz-carbonate veins present in both the altered and unaltered rocks suggests a relatively late-stage introduction of this material. (5) Contacts between fresh and altered rock are gradational rather than sharp.

A composite longitudinal section constructed using representative drillholes (Fig. 3), all inclined ca. 45° to the east, illustrates that 20-50% of the core is altered (note that it may reach 70% if the missing core is also altered rock) beneath the mineralized zone. Also shown in this diagram is the orientation of the fabric (seen in Fig. 5)

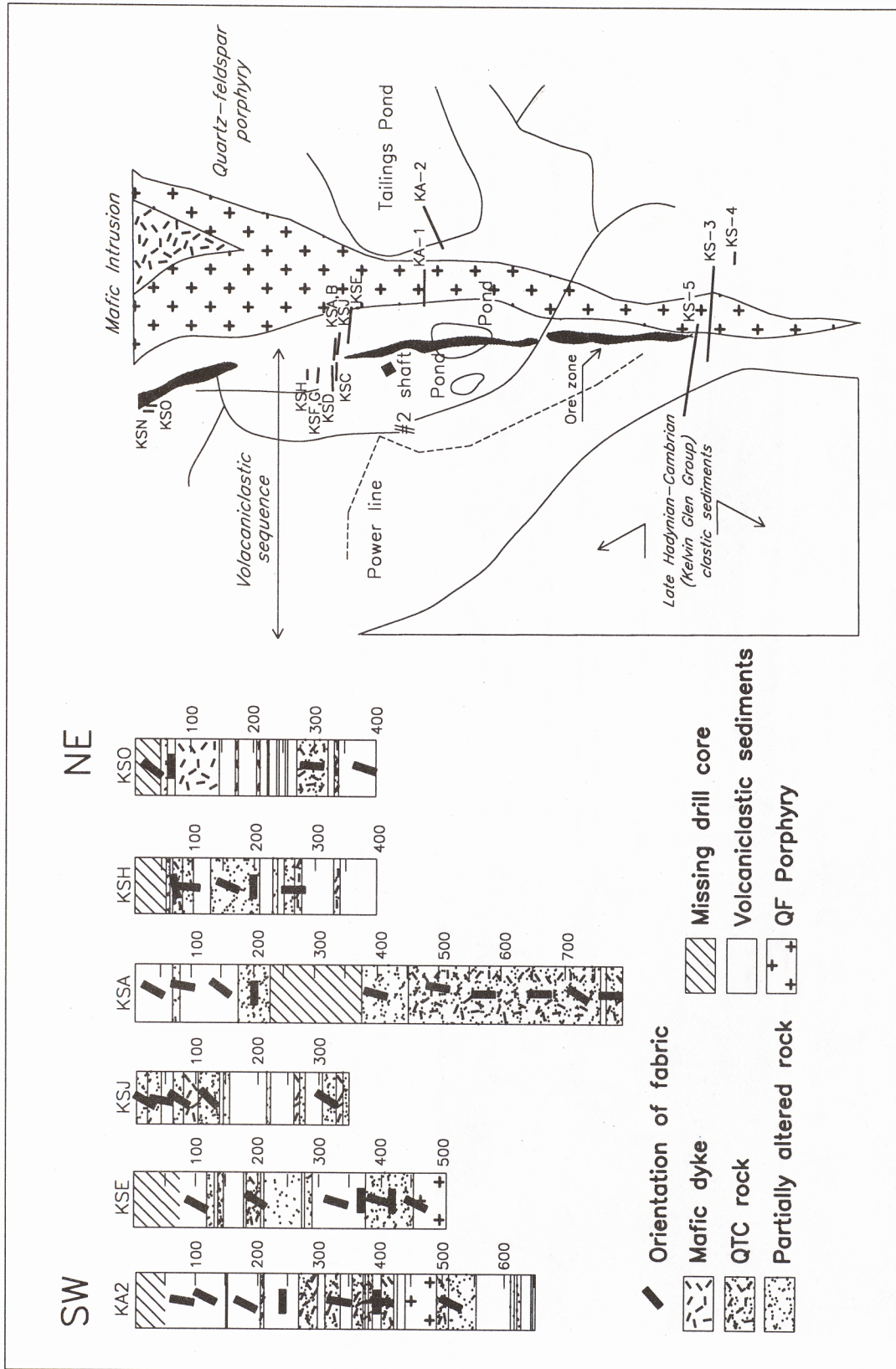


Figure 3. Map of the Stirling deposit area showing the outline of the quartz-feldspar porphyry unit, the ore zone and locations of drillholes that were logged. Representative, simplified logs for several holes are shown to illustrate the extent of alteration. Note that all holes were collared at a similar elevation and were inclined ca. 45 degrees to the east.



Figure 4. Photograph of diamond-drill core from hole KA-2 at the Stirling deposit. Each core length is ca. 1.5 m long and starts at 350 ft. in the lower right and goes to 400 ft. in upper left. Bleaching of the dark grey-green rock is due to variable amounts of quartz-talc-carbonate (QTC) alteration. Letters represent samples of the core that were analyzed for major and trace element chemistry (see Figs. 6, 7 and 8). Asterisk represents the point from which distances up-core were measured. Samples Q and R were taken from the next piece of core (above 350 ft.).



Figure 5. Photograph of diamond-drill core from hole KA-2 (box #14) at the Stirling deposit showing intense alteration of the host rock due to replacement by quartz-talc-carbonate rock. Note the well-developed fabric in the rocks and also late-stage quartz veins with alteration halos in the right end of the centre piece of core. Width of the core is ca. 3.5 cm.

relative to the core axes, which varies from oblique (30-40°) to parallel to the core axes. The orientation of this planar fabric varies down the holes and reflects folding, which appears to be considerable from the change in orientation of the fabric, and was likely isoclinal. The fact that the fabric is parallel to the core axis in hole KSA (Fig. 3) suggests that the abnormal thickness of the QTC rock in this hole may relate to drilling parallel to the fabric (layering) on the limb of a tight fold.

Lithochemochemistry

The results of major and trace element geochemical analysis (X-ray fluorescence at St. Mary's University, Halifax, Nova Scotia) and rare earth element (REE) analysis (ICP-MS, Memorial University, St. John's, Newfoundland) are presented in this section for drillhole KA-2. The major and trace element data are given in Table 1 and plotted in Figures 6 and 7, with chondrite-normalized REE plots shown in Figure 8. Additional data for volcanoclastic rocks and QTC rock are shown in Figure 9 for comparison to the alteration profile.

To ascertain the extent of geochemical enrichment and/or depletion, it is first necessary to establish which samples have retained primary geochemical signatures by using elements that are generally considered immobile. In this case, a plot of Ti/Zr versus distance up-core clearly indicates that the least altered samples, that is the darkest rocks in Figure 3 (A, B, E, P, Q and R; Fig. 6a), have retained a similar Ti/Zr ratio, whereas the altered samples have a much different signature due to the depletion of Ti (Fig. 7c). A similarly consistent pattern emerges in many other plots. (1) The transition elements (Ni, Cr, Co, V, Sc; Fig. 6b), Al_2O_3 (Fig. 7a), Fe_2O_3 (Fig. 7b) and Na_2O (Fig. 7c) behave similarly and follow the pattern established by Ti/Zr with depletion in the altered samples. The consistent trend for Al_2O_3/Fe_2O_3 (Fig. 7d) attests to the similar behaviour of these elements. (2) Absolute values of Zr (also, Y and the HREE) increase in the altered samples, whereas Nb shows the depletion trend similar to Ti (Fig. 6c). (3) Although Na_2O parallels the trend for Ti/Zr, K_2O departs from this and shows variable enrichment in the altered samples (Fig. 7c). (4) Calcium (CaO) shows

Table 1. Geochemistry for alteration profile in DDH KA2, Stirling deposit, southeast Cape Breton Island.

Sample No.	STB-98-A	STB-98-B	STB-98-C	STB-98-D	STB-98-E	STB-98-F	STB-98-G	STB-98-H	STB-98-I	STB-98-J	STB-98-K	STB-98-M	STB-98-N	STB-98-O	STB-98-P	STB-98-Q	STB-98-R
distance (cm)*	2	5	8	14	25	28	31	34	45	50	57	76	85	90	97	102	115
SiO ₂	44.97	45.82	59.9	68.61	53.55	66.2	30.71	35.96	50.62	60.91	37.98	40.79	36.35	56.86	50.81	43.94	51.53
TiO ₂	0.744	0.764	0.139	0.137	0.82	0.184	0.103	0.103	0.146	0.122	0.113	0.107	0.096	0.127	0.759	0.831	0.798
Al ₂ O ₃	14.58	14.32	7.38	7.32	14.7	10.25	5.23	5.41	7.27	7.21	6.15	5.5	5.29	6.93	13.78	15.48	14.38
Fe ₂ O ₃	9.43	9.16	2.81	2.95	9.22	5.69	4.13	3.62	3.81	5.61	3.74	3.45	3.36	3.58	8.47	10.34	10.06
MnO	0.159	0.205	0.127	0.091	0.095	0.081	0.29	0.199	0.167	0.096	0.222	0.187	0.177	0.132	0.12	0.144	0.083
MgO	6.92	6.59	4.74	3.77	7.13	5.23	10.89	10.86	7.86	7.11	9.94	9.92	10.82	6.3	5.61	7.11	6.34
CaO	9.57	7.5	9.15	5.75	3.97	3.76	19.51	17.04	11.11	6.69	15.69	15.3	16.76	9.49	7.11	7.92	5.76
Na ₂ O	2.83	3.06	0.16	0.34	0.76	0.64	0.41	0.2	0.35	0.26	0.55	0.66	0.32	0.09	2.58	2.47	2.13
K ₂ O	0.62	0.79	2.15	1.74	1.73	1.5	1.31	1.53	1.81	1.06	1.52	1.32	1.45	1.88	1.07	1.14	1.02
P ₂ O ₅	0.068	0.076	0.018	0.019	0.087	0.024	0.017	0.016	0.017	0.02	0.018	0.018	0.017	0.021	0.096	0.087	0.083
L.O.I.	11.45	11.7	13.85	9.26	8.42	7.2	27.73	26.42	17.95	11.96	24.68	23.9	26.05	15.29	11	11.88	8.71
Total	101.34	99.98	100.42	99.98	100.48	100.75	100.33	101.35	101.11	101.04	100.60	101.15	100.69	100.7	101.40	101.34	100.89
CO ₂	7.34	8.66	12.37	7.6	4.4	4.62	25.4	22.57	14.64	10.2	22.57	22.17	22.53	12.77	7.82	8	5.21
H ₂ O																	
Sc	27	9	0	23	53	16	0	0	0	0	0	0	0	0	8	24	43
V	236	239	0	10	228	7	3	10	5	9	2	0	0	0	199	246	234
Cr	574	500	0	0	479	0	0	0	0	0	0	0	0	0	429	454	467
Co	48	36	0	1	40	13	1	3	3	4	1	0	1	2	32	43	45
Zr	40	45	231	237	48	301	159	165	233	208	184	176	170	149	43	41	46
Ba	227	82	315	157	246	105	227	221	361	266	245	146	132	369	68	66	75
La	6	0	8	15	0	23	11	11	31	16	7	13	16	27	2	0	0
Ce	0	0	20	66	0	0	42	0	18	0	34	36	24	0	22	0	26
Nd	7	14	17	31	16	27	19	14	24	20	17	18	7	17	7	0	0
Ni	69	60	15	42	59	69	10	3	13	20	1	10	24	33	52	54	56
Cu	41	40	8	7	88	7	32	11	9	15	13	9	18	10	64	66	88
Zn	99	188	74	114	528	353	89	217	181	424	115	115	111	127	233	216	522
Ga	12	12	17	13	16	19	10	7	17	14	9	11	9	10	12	15	15
Rb	36	40	78	75	56	63	51	59	68	55	59	57	58	71	46	42	42
Sr	112	96	81	51	42	42	148	143	94	63	131	126	137	86	87	78	68
Y	17	16	44	46	18	74	40	34	56	76	44	40	35	27	16	19	19
Nb	13	11	0	0	10	3	7	4	0	0	3	2	2	0	9	15	13
Sn	0	2	2	4	0	4	1	2	0	1	2	3	2	1	1	1	1
Pb	25	6	20	19	20	39	44	79	21	22	14	16	17	16	14	8	17
Th	1	1	1	1	2	5	4	3	2	2	1	3	2	3	1	0	0
U	0	1	0	0	0	2	0	0	0	1	0	0	0	1	2	0	0

*distance in cm from the spot marked * on core, Fig. 4; 0=below detection limit

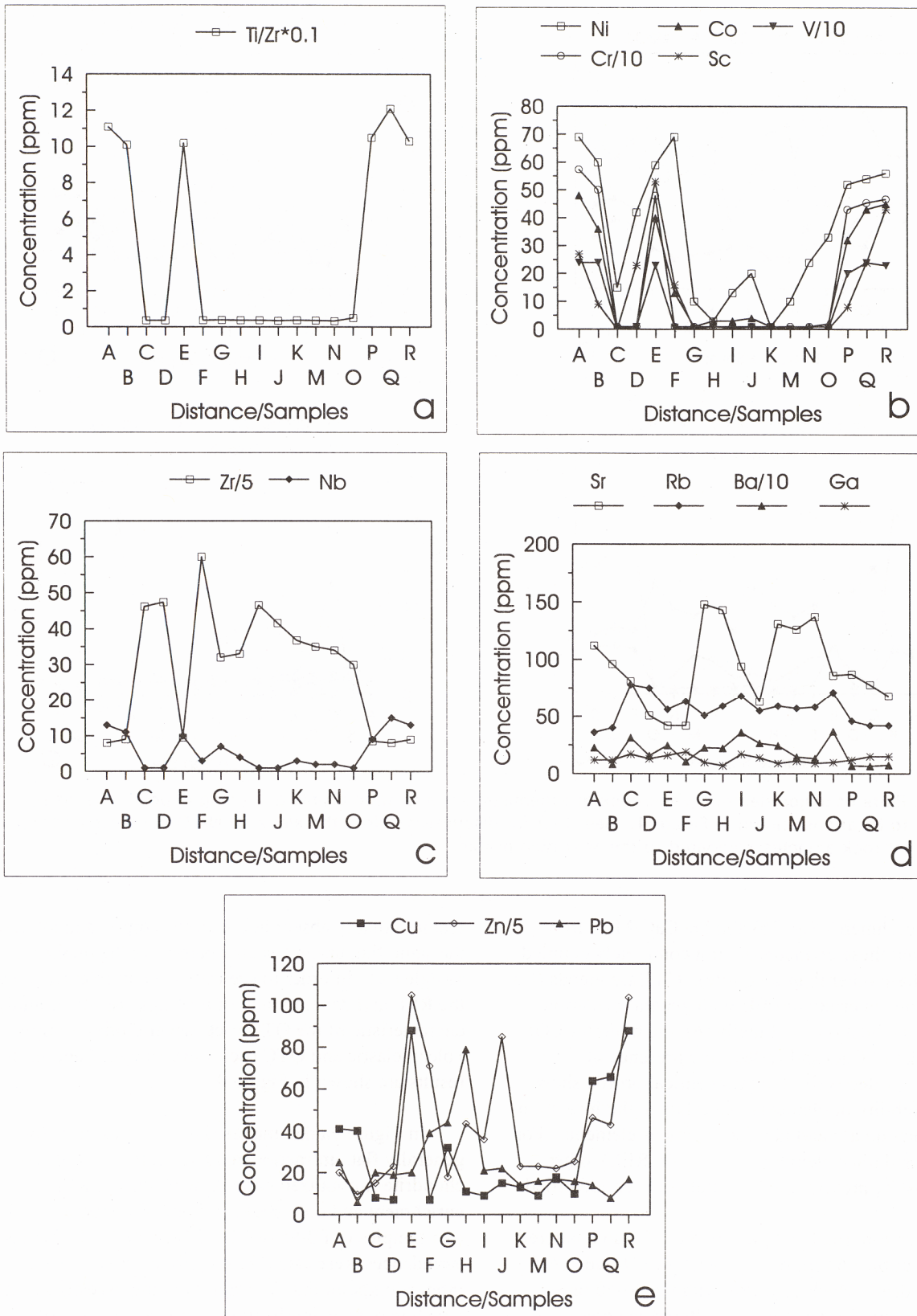


Figure 6. Plots of minor and trace element whole-rock geochemistry for alteration profile at Stirling deposit. Samples correlate to those shown in Figure 4. See text for discussion. Note the elevated Ti/Zr ratios for the least altered host rock samples compared to the alteration profile.

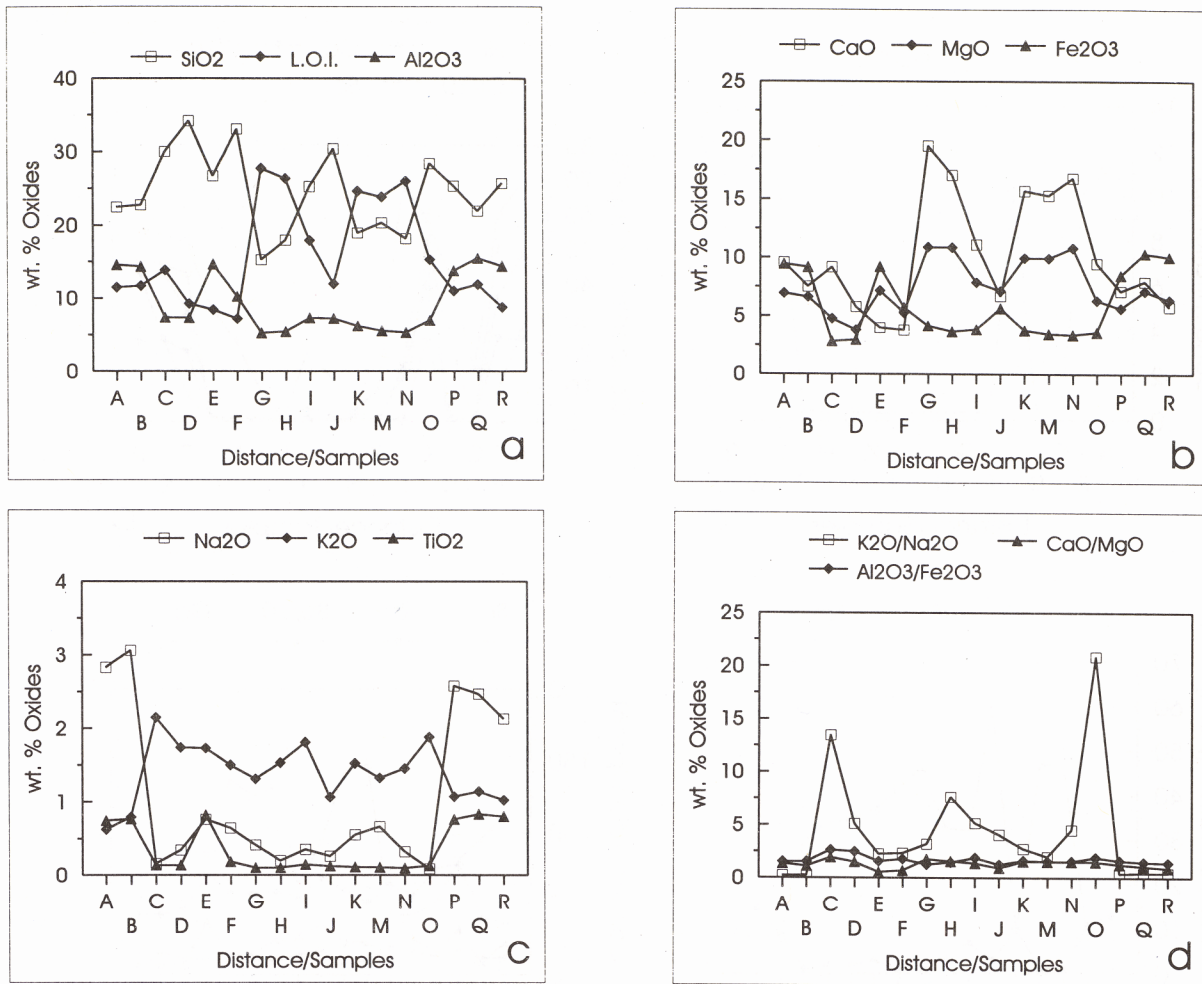


Figure 7. Plots of major element whole-rock geochemistry for alteration profile at Stirling deposit. Samples correlate to locations shown in Figure 4. See text for discussion. Note the elevated Na_2O contents of the least altered host rock samples compared to the alteration profile.

variable enrichment (Fig. 7b) and the CaO/MgO trend indicates that these elements are not completely coupled (i.e. in a phase other than dolomite). (5) Base metals (Cu, Pb, Zn) show an erratic profile with general depletion relative to the host rocks. Finally (6), the trend for LOI parallels that of CaO and reflects the presence of carbonate. Collectively, the geochemical profile shows variable mobility of elements that relate to the formation of carbonate, quartz and talc for the major elements. For the minor and trace elements (e.g. Y, Zr, REE), other phases must be present that have not yet been identified.

Chondrite-normalized plots of REE for an unaltered wallrock sample (A) shows a generally flat trend at 6-8 times chondrite, which contrasts with the 30-50 times chondrite normalized patterns for altered samples (C, I, M) (Fig. 8). In addition, the altered samples are all characterized by negative Eu anomalies ($\text{Eu/Eu}^* < 1$), a

feature notably absent in the fresh sample, and all have the same flat, unfractionated pattern as the unaltered sample (A). In order to see if this apparent enrichment of the REE and development of the negative Eu anomaly is characteristic of the QTC rock, several other samples of volcanoclastic and QTC rock were analyzed and these results are shown in Figure 9.

In Figure 9a the unaltered volcanoclastics show generally flat, unfractionated to slightly fractionated chondrite-normalized patterns with slight LREE enrichment and only slight negative Eu anomalies. The two samples (STB-98-1021, 1043) with the highest REE abundances were also proximal to the ore zone, an interesting point that is currently being investigated and which may have implications for identification of mineralizing processes. In Figure 9b the chondrite-normalized REE plots for QTC rocks are shown,

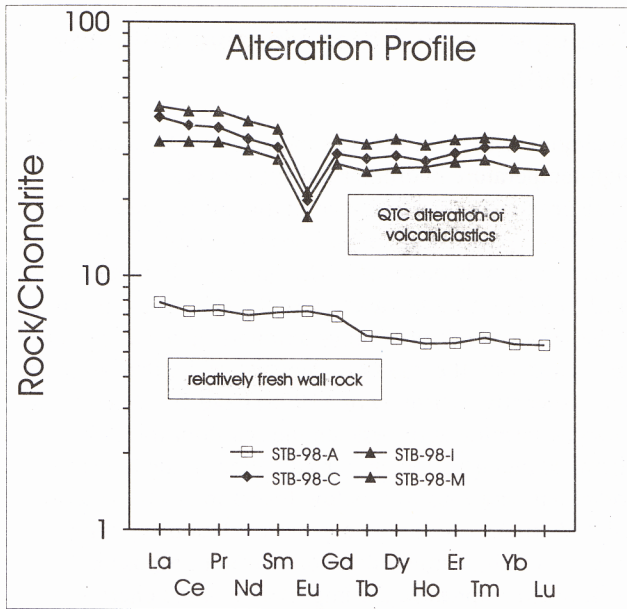


Figure 8. Chondrite-normalized rare earth element plot for relatively fresh host rock (wallrock) and quartz-talc-carbonate altered rocks from diamond-drill hole KA-2.

including samples (STB-98-C, I, M) from the alteration profile for comparison. Collectively the data show a range from ca. 1 to ca. 60 times chondrite abundances, and only samples in excess of 10 times chondrite have negative Eu anomalies. The simple scenario apparent for the alteration profile, with REE enrichment accompanying alteration, may be an artifact of limited sampling, or enrichment of the REE and development of a negative Eu anomaly may relate to hydrothermal activity as per the discussion about samples STB-98-1021 and -1043. Clearly, further investigation of this data set is warranted and any conclusions are premature at this stage.

Discussion

Alteration Origin for QTC Rock

The presence of intense bleaching of volcaniclastic host rocks beneath the ore zone at the Stirling massive sulphide deposit has been documented. The presence of quartz-carbonate-talc (QTC) rock forming extensive alteration zones which post-date sulphide mineralization (Kontak, 1998) is a marked change from previous interpretations that QTC rock represents syngenetic accumulations of this material on the ocean floor. However, at one locality there is compelling evidence for syngenetic accumulation of QTC rock at or near the ocean floor (Kontak, 1999). Based on logging of drill core, alteration is estimated to extend the length of the

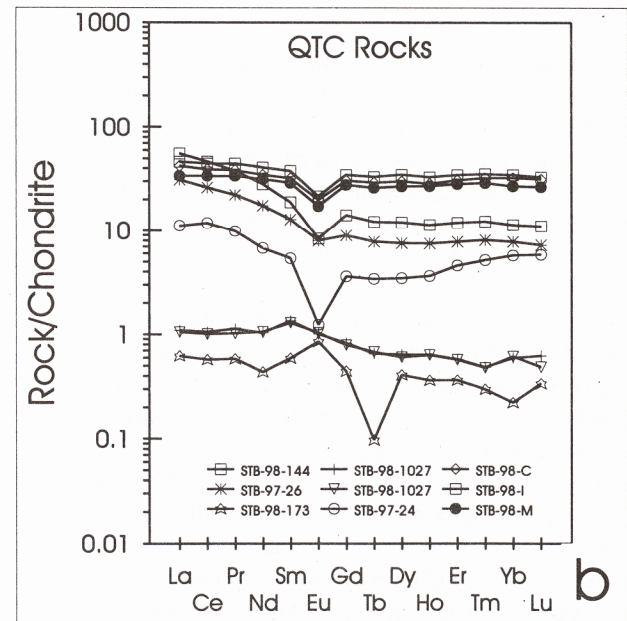
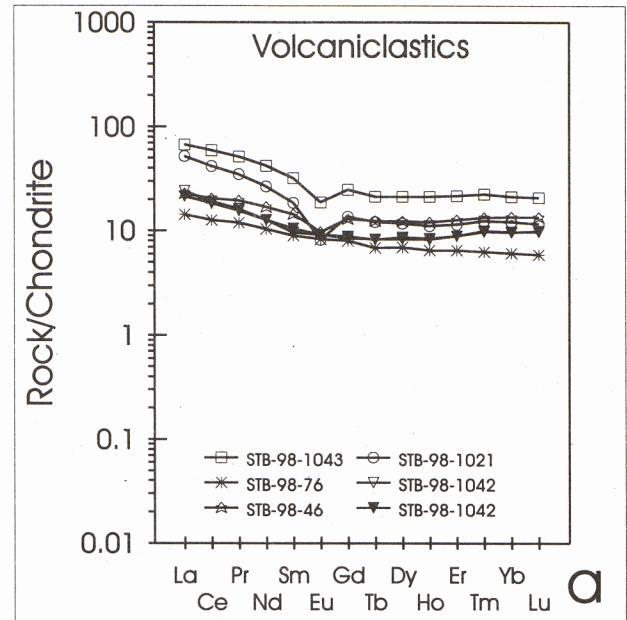


Figure 9. Chondrite-normalized rare earth element plots for relatively fresh volcaniclastics and QTC rocks from the Stirling deposit. Note that there is a large range in the data for the QTC rocks compared to the fresh volcaniclastics.

area shown in Figure 3 and it may in fact continue to the east and west. The apparent thickness is up to 100 m, but this is complicated by structure, as noted above with reference to drillhole KSA (Fig. 3). This same alteration also extends into the porphyry unit at depth, based on observations and subsequent geochemistry (unpublished data of Kontak). Thus, the amount of material affected by fluid:rock interaction has been considerable.

Lithochemistry of an alteration profile indicates extreme enrichment and depletion of many elements, including some that are generally considered to be immobile during alteration (e.g. Ti, Zr, REE). The apparent lack of any conserved elements throughout the alteration profile precludes determination of gains and losses of material (e.g. Grant, 1986). However, the presence of well-developed, primary layering throughout fresh and altered sections of drill core suggests that alteration was a constant volume process. Thus the relative gains and losses are real and not related to changes in rock volume, although some may be attributable to a change in rock mass. The deposition of carbonate-rich material occurred in alkaline conditions, which contrast markedly with the acid-dominated systems associated with most alteration environments and massive sulphide deposits (Franklin, 1993). It is thus pertinent to note that mobility of many of the 'immobile' elements (e.g. Ti, Nb, Zr, REE) has been documented in alkaline environments.

Among the major and minor elements the most enriched are CaO, MgO, SiO₂ and K₂O, whereas the most depleted are Na₂O, Al₂O₃ and TiO₂. The mineralogy of the alteration zone, consisting of carbonate, quartz and talc, reflects this chemical signature except for K₂O, which suggests the presence of a white mica phase. Depletion of Al₂O₃ reflects the breakdown of feldspar and chlorite in the host rock. The relative enrichment of all the REE without any apparent fractionation indicates inheritance of this pattern from the host rocks and also requires very large amounts of fluid (high fluid:rock ratios). The presence of a negative Eu anomaly in the altered rocks is a reflection of the redox state of the fluid and hence dominance of Eu²⁺ over Eu³⁺. The absence of a Ce anomaly, characteristic of marine sediments and ocean water, precludes involvement of unmodified seawater in generation of the QTC rock, which is also consistent with the negative Eu anomalies. Instead, formation of the QTC rock involved passage of a fluid that exchanged and equilibrated with rocks at depth, although it may originally have been ocean water.

The combination of visual observations, petrographic examination of thin sections, and lithochemistry of the QTC rock from drill core is interpreted to indicate an origin by variable replacement of the volcanoclastic host rock. Further work is focusing on the nature and origin of the QTC rock in order to better define its origin and determine what role it played in the formation of the Stirling massive sulphide deposit.

Analogies with Other Massive Sulphide Deposits

Analogies with other districts indicate that both low- and high-temperature hydrothermal systems may exist in close proximity, as mentioned in the introduction with reference to the Errington and Vermilion Zn-Cu-Pb massive sulphide deposits of the Sudbury district (Rousell *et al.*, 1997). Another analogy to the QTC rock at Stirling is the presence of voluminous amounts of secondary chert associated with the giant ore deposits of the Iberian pyrite belt. Recently, Leistel *et al.* (1998) have described these rocks as forming at or beneath the sea floor through chemical precipitation and/or alteration of the host rock and at temperatures well below formation of the massive sulphide rocks. Although a genetic relationship with massive sulphide mineralization was not proposed, the authors did emphasize the importance of the chert as a paleodynamic indicator (i.e., if the chert is present then so might there be massive sulphide). A similar approach is tentatively proposed for Stirling, with the QTC rock an indicator of the appropriate paleotectonic setting for massive sulphide mineralization.

In summary, an alteration origin is proposed for quartz-talc-carbonate rock at the Stirling deposit, although this does not exclude the potential for a small amount of exhalative material cogenetic with formation of the sub-sea floor alteration zones. Modern analogues such as calcareous sinters or travertine suggest a low temperature origin for the QTC rock, which contrasts with higher temperatures generally inferred for massive sulphide formation. Thus, two competing hydrological systems are considered to have coexisted spatially and temporally and may have been related to the presence of an underlying felsic magma represented today by a large body of quartz-feldspar porphyry. Similarities of the setting of the Stirling district to other massive sulphide camps with variations on the quartz-carbonate-talc alteration style (e.g. Sudbury area, Sweden, Iberia) suggest a high potential for the Stirling area.

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