WALL ROCK ALTERATION

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ABSTRACT

Alteration zones bordering the veins of the Cobalt-Gowganda region typically consist of a dark albite-chlorite assemblage followed outward by a sericitic zone. A light-coloured band of dolomite-calcite (± epidote), which generally occurs between the albite-chlorite and sericitic zones, is believed to have been superimposed during carbonate gangue deposition.

Chemical analyses and specific gravities of the alteration zones and the unaffected wall rocks indicate that alteration has occurred with little volume change. The chemical exchanges are reflected in the changed mineralogy, but the sequential nature of alteration development is obscured in the bulk analyses. Mineral stability relationships indicate that temperature or the Na^+/K^+ activity ratio was generally higher adjacent to the veins than further in the wall rocks. Microprobe analyses of chlorites and carbonates do not show well-defined compositional trends. Leaching of magnetite from the wall rocks suggests that high oxygen/sulphur fugacities prevailed during alteration, but a reversal occurred with the onset of ore deposition.

INTRODUCTION AND PREVIOUS STUDIES

Narrow altered zones adjacent to veins are readily recognized in most host rocks in the Cobalt-Gowganda region. The wall rock alteration commonly consists of an outer light-coloured zone which is gradational to a dark band adjacent to the vein. Each of the zones is usually no more than a few centimeters wide, and under normal conditions each zone symmetrically flanks a vein.

The potential importance of alteration studies in contributing toward knowledge of the nature of the ore-forming process is well-known. In the Cobalt-Gowganda region, alteration along the silver veins was first described by Bastin (1935, 1939), and additional data were subsequently contributed in theses by Bourne (1951), Parkinson (1951), Scott (1964), and Dass (1970). These writers have recognized that there is albitization adjacent to the veins, and that the colour of the dark band bordering veins is largely due to the presence of chlorite.

Numerous chemical profiles extending more than a meter outward from veins are given by Dass (1970). In the present study it was recognized that the principal alteration effects occur within only a few cm of the veins, and attention has therefore been focused exclusively on this restricted width. The effects of wall rock alteration are best seen in the Nipissing diabase, but alteration is by no means restricted to this rock type. Proterozoic sediments and diverse Archean rocks also contain altered vein borders, the prominence of which is partly dependent on the chemical composition of the host rock.

General Features

Wall rock alteration is present along ore veins, and a variety of pre-ore joints and fractures, some of which have already been described (p. 72). Calcite penetration leading to a "bleached" appearance of the wall rocks along post-ore calcite-sulphide veins has also been observed, but has not been studied in detail.

In general, the size of the alteration bands is not dependent on the width or length of an ore-bearing vein or fracture. The maximum total width of the alteration zones is of the order of 30 cm and these widths are in some cases associated with mere hairline fractures. A coloured zonal

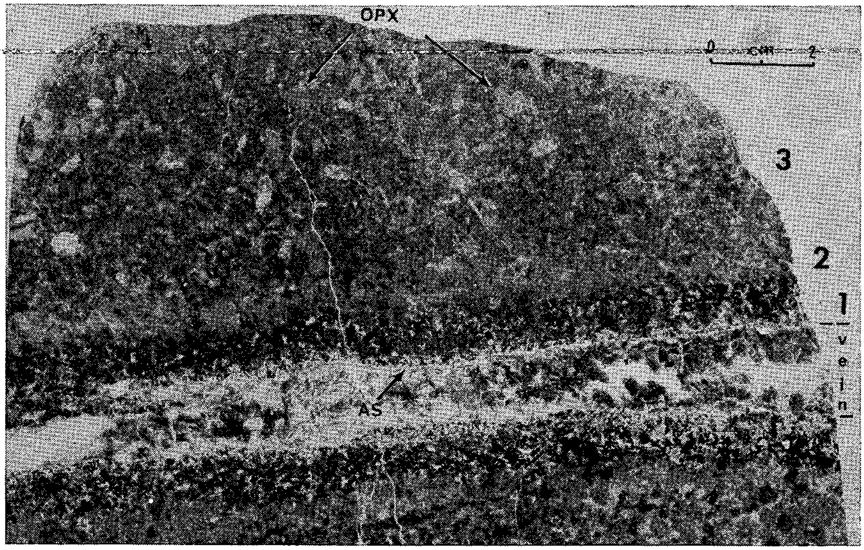


Fig. 181. Silver-arsenide vein in hypersthene diabase (JF66-26) from the Castle No. 3 shaft, Miller L., Gowganda. Large grains of orthopyroxene (OPX) are visible throughout the least altered upper half of the specimen (zone 3). A light-coloured mafic-poor zone (2) adjoins the mafic-rich zone (1) bordering the vein. Arsenides (AS) occur along the vein wall as a discontinuous film, 1-2 mm thick. Finely disseminated arsenides, with some silver, occur in the vein and give the calcite a dark grey mottled appearance. GSC photo 201291F.

pattern, which reflects a changed mineralogy and chemistry, is usually evident in the altered rock; this zonal arrangement is very commonly bilaterally symmetrical. Most veins have, however, been subjected to reopening and renewed mineral deposition. In many cases this has occurred along only one of the vein walls so that the bilateral symmetry has been distorted or completely destroyed.

The over-all trend in the veins of the region is to have convergent alteration, that is, diverse wall rock types are modified in such a way that the attainment or approach toward a uniform rock type is the end result. The mineralogical expression of this end product is normally to have albite, chlorite, and calcite formed in the wall rocks close to the veins. For most of the Nipissing diabase, which is rich in calcic plagioclases, orthopyroxenes, and clinopyroxenes, the assemblage of albite-chlorite-calcite which is associated with vein deposition is drastically dissimilar. Wall rock alteration effects in the diabase are therefore characteristically prominent, particularly in the least salic fractions of this rock. In many Proterozoic sediments, however, quartz, albite, and chlorite already constitute the predominant mineral assemblage; less chemical change is therefore necessary to attain equilibration toward the characteristic wall rock alteration mineral suite. Thus, in many Cobalt sediments the alteration zones are not strongly developed, the main effects being an introduction of calcite and additional chlorite (plus ore minerals). The Archean rocks are of diverse types, but the same principles seem to be valid. The chemical analyses given by Dass (1970) confirm that little exchange has occurred in some cases, but in others the effects of alteration are easily recognized.

It has been difficult to determine whether the gangue minerals systematically vary in composition laterally and vertically in a vein. No equivalent study of the wall rock alteration has been done, but the results of the present work have not indicated that such an undertaking would be particularly fruitful.

EXAMPLES OF WALL ROCK ALTERATION

Common types of alteration

Almost all diabase is partly altered by deuteric effects so that caution is necessary in distinguishing the minerals already present in the rock from those formed during the wall rock alteration process. The commonest type of wall rock alteration associated with ore veins in the Nipissing diabase is shown in Figure 181. In the outermost, "unaltered" part of the rock (zone 3, Fig. 181), the principal minerals are zoned calcic plagioclase (up to An 75), augite, and numerous scattered large grains of orthopyroxene, a few of which are partly rimmed by inverted pigeonite with blebby exsolution. Plagioclase is the most altered mineral, with most grains being at least partly replaced by extensive sericitization ($2M_1$ muscovite). Replacement has been predominantly from the cores toward the more sodic rims. Clinopyroxene is relatively fresh, but replacement of zoned orthopyroxene by calcite and a little talc is slightly greater than normal. The small amounts of interstitial quartz and primary amphibole have not been affected. In summary, the outermost parts of the specimen probably contain some wall rock alteration effects; these are the heavier-than-normal sericitization and the partial replacement of orthopyroxene by calcite.

In the light-coloured zone (2) both orthopyroxene and clinopyroxene have been completely replaced, but their grain outlines and the texture of the rock are still preserved. The pyroxene pseudomorphs are very fine-grained turbid calcite which contains some chlorite as indicated by x-ray powder photographs. Partly sericitized remnants of zoned plagioclase grains are still visible, but a significant change is the appearance of albite as irregular, ragged patches amongst the sericite and at some of the feldspar grain boundaries. The change from this carbonate-rich zone to the dark zone (3) bordering the vein is relatively abruptly marked by chlorite in place of the calcite pseudomorphs of the pyroxenes. The original pyroxene grain boundaries and twinning are preserved, but additional chlorite replacement of the feldspars has resulted in some deterioration of the original texture of the rock. In addition to chlorite, the most abundant minerals present are albite and calcite. The albite is tinged pinkish from very fine hematitic dust. Grain boundaries are typically serrate as a result of their replacement by calcite and chlorite, with both also occurring in irregular patches throughout the feldspar. Twinning on a very fine scale (Figs. 182, 183) adds to the complex appearance of the grains. Numerous disseminated arsenide grains have penetrated well into the zone. A few scattered grains of quartz with ragged boundaries and a bit of anhedral sphene complete the mineralogical make-up of the band.

FIG. 182. (Left) Complexly-twinned albite with chlorite (Ch) at vein margin. Transmitted light, crossed nicols.

FIG. 183. (Right) Typical complex twinning in albite in albitized wall rock. Transmitted light, crossed nicols. Width of scale line 0.1 mm.

Microprobe analyses of 3 chlorites, of which 2 are from the dark zone bordering the vein, are given in Table 64. Spot checks on additional grains show that there is a difference in composition between the chlorite pseudomorphs in the wall rock and the sheaf-like chlorite deposited along the vein wall. X-ray powder photographs indicate that the vein chlorite is the IIb polytype (Bailey & Brown 1962), whereas the pseudomorphs belong to the I class (the specific type not being identifiable because of the inadequate quality of the powder photographs). Although microprobe analyses indicate that small variations in Fe, Mg, and Mn are present both in the vein and wall rock calcites, the sum of these cations is considerably less than 1 per cent.

In summary, the principal alteration effects are the development of a dark, albite-rich, chlorite zone at the vein margins, and a light, carbonate-rich zone farther from the vein. Sericitization of the plagioclases is present in the carbonate-rich zone and gradually decreases outwards to relatively "unaltered" diabase. Chemical analyses of the altered and relatively fresh diabase are given in Table 65.

TABLE 64. MICROPROBE ANALYSES OF CHLORITES IN ALTERED HYPERSTHENE DIABASE FROM THE CASTLE NO. 3 SHAFT, GOWGANDA (SPECIMEN JF66–26).

Wt. %	Radiating sheaf at vein margin	Compact pseudomorphs after clinopyroxene Dark zone (1)	 Between (1) and (2) zones
SiO_2	30.9	27.9	30.3
Al_2O_3	17.7	19.2	18.2
MgO	20.0	28.4	22.6
FeO*	23.2	15.7	21.2

Analyst: A.G. Plant * Total Fe as FeO

TABLE 65. CHEMICAL ANALYSES OF ALTERATION ZONES IN NIPISSING DIABASE (JF66–26) FROM THE CASTLE NO. 3 SHAFT, HAULTAIN TOWNSHIP, GOWGANDA.

Wt. %	1 dark (albite-chlorite zone)	2 light (calcite-sericite zone)	3 "un-altered" diabase	ppm	1	2	3
SiO_2	40.9	34.8	46.5	Rb	NF	100	75
Al_2O_3	17.0	15.9	15.1	Sr	45	100	45
Fe_2O_3	2.6	0.4	0.8	Cr	720	260	200
FeO	11.2	4.5	5.5	Co	330	NF	NF
MnO	0.29	0.26	0.14	Ni	100	120	120
MgO	8.1	4.6	9.0	Cu	40	400	90
CaO	5.3	16.9	10.4	Ag	160	100	NF
Na_2O	4.1	2.6	1.8	Zn	380	280	50
K_2O	0.3	2.4	2.2	Pb	140	460	NF
TiO_2	0.35	0.32	0.27	As	1700	350	200
H_2O	6.6	3.2	2.5	Sb	30	50	NF
CO_2	3.8	11.5	1.7	Sp. Grav.	2.780	2.790	2.957
S	0.02	0.01	0.02	CaO less $CaCO_3$	0.5	2.2	8.2
Sum	100.6	97.4	95.9				

In this paper all analyses and specific gravity determinations (pycnometer) are by the Rapid Methods Group, Analytical Chemistry Section, GSC. Accompanying trace element determinations (XRF) are by J. Gravel, Mineralogy Section, GSC.

K-feldspar alteration

Although most veins are accompanied by albitized alteration zones, in some the alteration process has led to the development of K-feldspar. Figure 184 shows part of an ore vein which extends from Nipissing diabase into the underlying Archean volcanics in the Lower Bonsall mine, Gowganda. Wall rock alteration in both rock types is of narrow width and is characterized by being rusty red in colour.

Chemical analyses of the Archean and Nipissing host rocks are given in Table 66. The principal constituents of the Archean metavolcanic rock are very fine-grained actinolite, albite, chlorite, quartz, and K-feldspar. Little change is evident until the reddish K-feldspar borders of the vein are reached. In this zone (column 1, Table 66) the principal minerals are K-feldspar, calcite, and chlorite, with amphibole being absent. Most K-feldspar grains are characterized by having highly irregular, serrate margins, and all lack uniform extinction. X-ray diffractometer studies indicate that the feldspar belongs to the maximum microcline-low albite series, and microprobe analyses show that the mineral is almost pure K-feldspar. The reddish colour is attributable to very fine particles of iron oxide in the microcline. The alteration zone is highly fractured and cut through by chlorite, calcite, and ore minerals. The chlorite is in compact masses and is a one-layer polytype.

The chilled Nipissing diabase consists of compactly intergrown plumose feldspars having a length of less than 0.15 mm. Fine-grained calcite aggregates and sphene, the latter averaging about 0.01 mm in diameter, are scattered throughout the groundmass. Chlorite is very abundant in a 2-3 mm wide zone abutting the vein and is followed outward by the reddish zone represented by the first diabase analysis in Table 66. Micro-

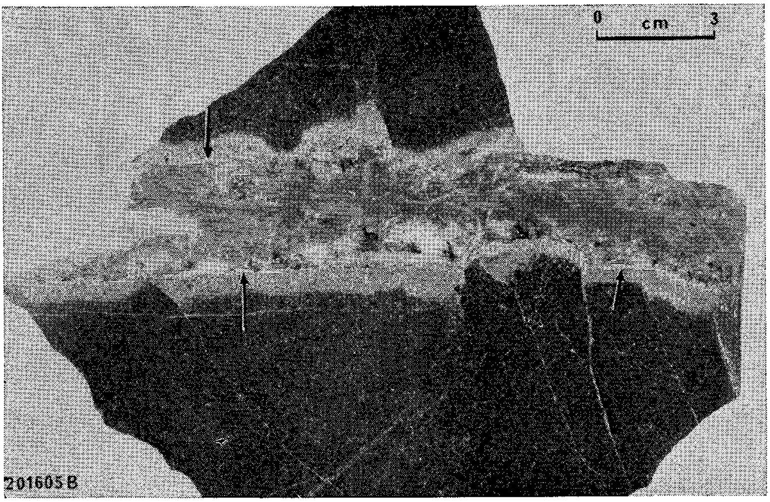


FIG. 184. Arsenide ore vein in Archean host rock, with prominent pinkish K-feldspar alteration margins. Arrows point to a thin, discontinuous layer of K-feldspar deposited on the wall rock. (JF69G-70, Lower Bonsall mine, Miller Lake, Gowganda).

TABLE 66. K-FELDSPAR WALL ROCK ALTERATION IN ARCHEAN VOLCANICS AND NIPISSING DIABASE.

	Lower Bonsall mine, Miller Lake basin, Gowganda						*New Violet shaft, Cobalt*	
	Archean (Figure 184) JF69G–70			Nipissing diabase JF69G–76			Archean flow JF66–90	
Wt %	K-feldspar zone	inter-mediate	"un-altered"	K-feldspar zone	inter-mediate	"un-altered"	light zone	"un-altered"
SiO_2	41.1	47.7	48.5	51.7	56.6	50.5	56.2	58.8
Al_2O_3	11.8	9.6	9.7	16.9	16.8	15.7	13.3	15.6
Fe_2O_3	<0.1	1.9	2.8	0.8	2.0	2.4		0.6
FeO	3.0	10.8	11.7	4.8	5.8	8.2	10.6	5.4
MnO	0.34	0.35	0.34	0.11	0.13	0.19	0.26	0.21
MgO	1.5	8.2	8.8	3.7	5.5	7.9	2.9	2.7
CaO	15.8	10.4	9.4	3.5	1.6	3.3	3.8	4.2
Na_2O	0.8	2.0	2.1	3.2	4.5	4.2	2.6	5.5
K_2O	8.6	1.9	1.4	6.9	3.2	1.0	3.7	0.5
TiO_2	1.11	1.11	1.12	0.73	0.76	0.77	1.56	1.56
H_2O	1.7	2.5	2.6	2.9	4.0	4.9	2.6	2.4
CO_2	12.7	2.2	0.8	2.3	0.6	0.3	1.0	1.1
P_2O_5	0.12	0.11	0.08	0.07	0.07	0.07	1.32	0.04
Sum	98.6	98.8	99.3	97.6	101.6	99.4		98.6
ppm								
Rb	135	<30	<30	160	80	30	70	<30
Sr	75	30	<30	40	45	65	30	50
Cr	400	520	480		240	320	NF	NF
Co	270	NF	<30		NF	<30	2600	NF
Ni	100	90	100		70	100	NF	<30
Cu	1760	770	280		NF	<30	40	180
Ag	NF	NF	NF		NF	NF	NF	<30
Zn	NF	40	50		<30	60	45	100
Pb	1800	70	40		<30	120	360	60
As	750	<30	30		90	100	22,000	250
Sb	NF	<30	<30		<30	<30	300	NF
Sp. Grav.	2.688	2.981	3.036	2.674	2.713	2.788		
CaO less $CaCO_3$	—	7.6	8.4	0.6	0.8	2.9	2.5	2.8

probe analyses have confirmed that the high potash content is due to the presence of K-feldspar, and the high sodium content is attributable to albite.

Not all K-feldspar alteration is characterized by the presence of reddish colouration. A fine-grained Archean flow from the New Violet shaft at Cobalt (Table 66) contains a mineralized 3-4 cm wide calcite vein bordered by an irregular, fractured, 2 cm wide white band of K-feldspar alteration. The rock is similar in texture to the afore-mentioned chilled diabase. The high sodium content of the "unaltered" metavolcanic is due to fine-grained albite.

As a final example of altered rocks containing K-feldspar, a specimen of spotted Gowganda sediment from Cobalt is shown in Figure 185. The alteration effects are considerably more spectacular in the hand specimen than in thin section. K-feldspar occurs in highly irregular grains between the wall rock and the vein. The character of the grains initially suggests that they might be unreplaced or recrystallized clasts, but the preponderance of such grains along vein walls and the lack of recrystallization in the sedimentary groundmass do not support such a conclusion. The blackness of the wall rock at the vein borders reflects an increase in chlorite abundance, but the grain size is the same as that in the rock matrix. Carbonate stringers and replacement of the wall rock are largely (or wholly) calcite, not dolomite. Most stringers and carbonate patches are rimmed by a 0.05 mm layer of turbid, granular sphene which has been swept from the surrounding groundmass. Along the larger veins the sphene is present in the wall rock exactly at the contact with the vein. Relative to this reference line, the K-feldspar is in the vein rather than in the wall rock.

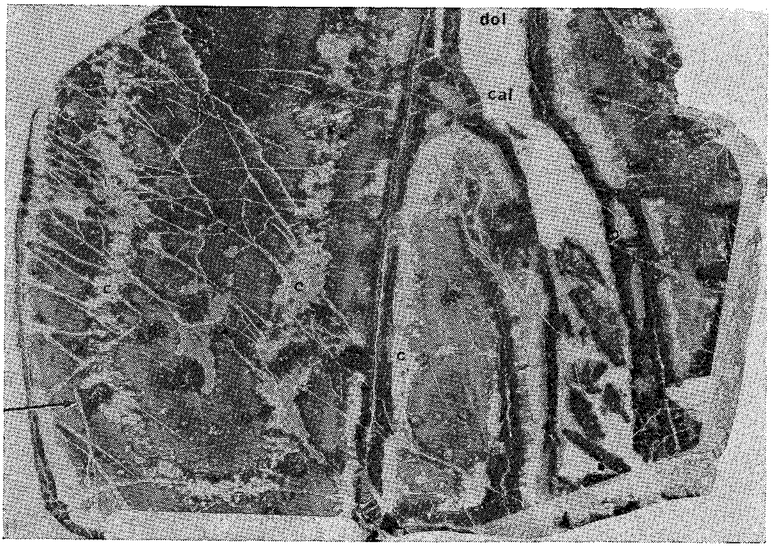


FIG. 185. Wall rock alteration in spotted Gowganda greywacke from the Right of Way (South mine), Coleman tp., Cobalt. Black chlorite alteration borders dolomite-calcite veins and stringers. The dolomite (dol) is pink and extensively replaced by calcite (cal) which is more translucent and appears slightly darker. Irregular light patches and stringers (c) in the wall rock are calcite-rich. Their white outlines, as indicated by the arrow at the lower left, are concentrations of sphene. GSC photo 201241D.

Epidote alteration

Some veins contain epidote in the light-coloured, carbonate-rich alteration zone. A specimen of hypersthene-bearing diabase with bilaterally-symmetrical alteration zones along a quartz-carbonate vein is shown in Figure 186. Only minute specks of sulphides and arsenides are present.

The outermost zone (3, Fig. 186) is diffuse and megascopically marked by a change in the felsic constituents to a greenish, greasy lustre. In thin section the principal changes are the increased sericitization of the plagioclase and the increased turbidity of the pyroxene. The change to the light-coloured band (zone 2) is marked by the appearance of epidote and calcite in such abundance that obliteration of the original rock texture has occurred. The epidote is in subhedral grains which range from 0.03 to 0.2 mm in maximum dimension. Zoning in the form of a single, lower-birefringent rim is clearly visible in many of the larger grains.

Epidote and calcite decrease toward the vein, with plagioclase and chlorite being the principal minerals in zone 1. The chlorite is present both as compact pseudomorphs of the original clinopyroxenes, and as small aggregates between grain boundaries and scattered throughout the plagioclase. All the non-sericitized parts of the feldspar have been converted to albite, but interstitial quartz seems to have been unaffected by the alteration processes.

The boundary between the wall rock and the vein is relatively sharp. The sequence toward the centre of the vein is chlorite (± quartz), quartz, and dolomite which has been extensively replaced by calcite. A small (< 1 mm wide) parallel veinlet of prehnite

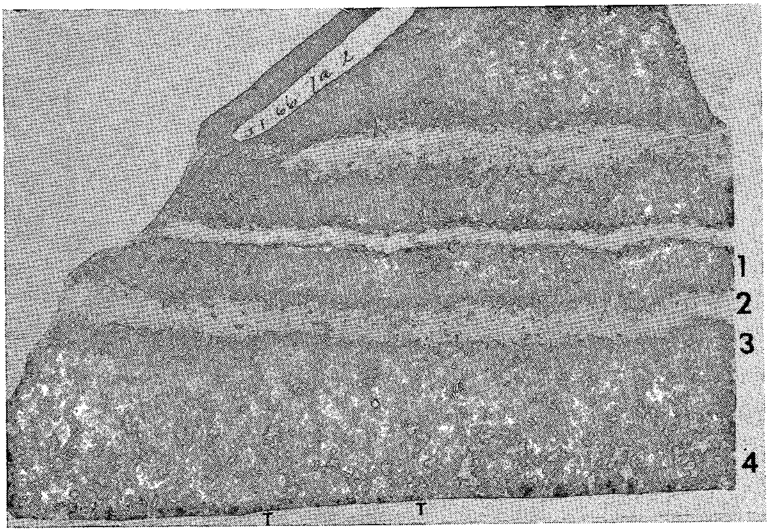


FIG. 186. Alteration zones along a quartz-carbonate vein in diabase from the Hargrave property, Coleman tp., Cobalt. A chlorite-albite zone (1) is succeeded by a calcite-epidote zone (2), which is followed by a diffuse zone of sericitization (3). Parts of the specimen were taped prior to etching with dilute HCl and staining with alizarin red. The right side of the rock and the vertical strip of width T-T show the unstained rock; carbonate-rich areas in the stained portions are whitened. (Basal width of specimen 13 cm). GSC photo 200352H.

TABLE 67. CHEMICAL ANALYSES OF ALTERED ZONES IN DIABASE (JF66–7a, FIG. 186) FROM THE HARGRAVE PROPERTY, SW 1/4, LOT 2, CONC. IV, COLEMAN TP., COBALT

Wt. %	1 Inner dark	2 Light	3 Outer dark	4 "Un-altered"	ppm	1	2	3	4
SiO_2	46.0	38.9	49.1	46.7	Rb	NF	NF	50	60
Al_2O_3	19.4	20.5	19.6	19.1	Sr	30	120	50	110
Fe_2O_3	1.0	3.4	1.2	1.5	Cr	120	<30	200	120
FeO	9.8	2.0	6.4	5.2	Co	NF	60	NF	NF
MnO	0.17	0.08	0.13	0.13	Ni	85	65	80	85
MgO	7.3	2.1	6.1	6.1	Cu	120	540	110	150
CaO	4.1	21.5	7.0	10.2	Ag	NF	<30	NF	NF
Na_2O	3.4	0.9	2.0	2.0	Zn	45	NF	<30	<30
K_2O	0.7	1.2	2.1	1.6	Pb	NF	NF	NF	NF
TiO_2	0.57	0.42	0.48	0.45	As	150	330	150	140
H_2O	5.5	2.3	3.9	2.6	Sb	NF	40	NF	NF
CO_2	1.7	6.5	1.0	0.3	Sp. Grav.	2.812	3.052	2.863	2.944
S	0.02	0.06	0.01	0.06	CaO less $CaCO_3$	1.9	13.2	5.7	9.8
Sum	99.7	99.9	99.0	95.9					

TABLE 68. CHEMICAL ANALYSES OF ALTERATION ZONES IN NIPISSING DIABASE (FIG. 187) FROM THE COLONIAL MINE, COBALT.

Wt. %	1 Dark	2 Light	3 "Un-altered"	ppm	1	2	3
SiO_2	48.1	38.0	50.6	Rb	NF	<30	50
Al_2O_3	15.4	15.0	14.8	Sr	60	420	60
Fe_2O_3	0.1	3.1	1.0	Cr	<30	<30	<30
FeO	10.2	3.6	8.8	Co	1800	50	NF
MnO	0.16	0.11	0.20	Ni	160	60	65
MgO	6.1	2.3	6.8	Cu	35	NF	320
CaO	5.9	21.3	6.7	Ag	30	<30	<30
Na_2O	3.6	2.6	3.5	Zn	65	NF	210
K_2O	0.1	1.1	1.3	Pb	NF	NF	NF
TiO_2	0.74	0.61	0.66	As	2800	650	450
H_2O	4.7	1.7	3.3	Sb	NF	NF	<30
CO_2	3.3	7.9	0.9				
S	0.19	0.03	0.05				
Sum	98.6	97.4	98.6				

and calcite cuts through the chlorite and quartz. Chlorite, both in the vein and altered zones, has olive-green interference colours and is uniformly the IIb polytype.

Chemical analyses of the 3 alteration zones and the relatively unaltered rock are given in Table 67. The presence of epidote in the light-coloured zone (column 2) is apparent from the excess of CaO relative to CO_2.

A similar mineralogy but a somewhat different appearance is shown by a specimen of medium-grained diabase in the varied-texture zone at the Colonial mine property, Cobalt (Fig. 187). The alteration progression is not much different from that just described.

The vein is quite narrow, but its minerals have a well-defined zonal arrangement. Chlorite is present along the walls and is succeeded by a medial seam of compact epidote granules. Where the vein widens, slightly elongate epidote grains form a continuous crustified layer along the chlorite-rich walls. The central part of the vein consists of abundant actinolite prisms and scattered crystals in calcite. The small gashes near the main vein (Fig. 187) also consist of calcite with small amounts of actinolite and traces of epidote.

Chemical analyses of the alteration zones are given in Table 68. The presence of epidote in the light-coloured zone is again readily apparent from the excess of CaO relative to CO_2. Also apparent in this rock, and in the one previously described above (JF66-7a), is the decrease in FeO and increase in Fe_2O_3 in the epidote zone.

Composition of epidote. Microprobe partial analyses of zoned epidote from the alteration zone in the Hargrave specimen (Fig. 186) are given in Table 69. The lower-birefringent rims contain less iron than the cores. The over-all trend is for iron to be highest in the vein epidote and lowest in the last-formed (rim) material in the wall rock. In the Colonial specimen (JF66-79, Fig. 187) the iron content is relatively high, but the difference between the vein and wall rock epidotes is small.

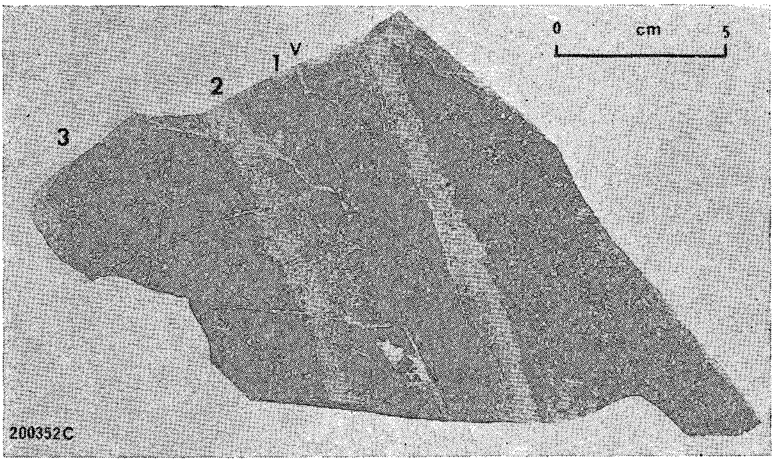


Fig. 187. Alteration bordering a small veinlet (v) in diabase from the Colonial mine, Cobalt (JF66-79). An albite-chlorite zone (1) grades into a green epidote-calcite zone (2). Subsidiary stringers and white patches of calcite are more abundant on the left side of the specimen.

TABLE 69. MICROPROBE PARTIAL ANALYSES OF VEIN AND WALL ROCK EPIDOTES

	JF66–7a (Fig. 186)			JF66–79 (Fig. 187)	
	in	zoned, in wall rock		in	in
Wt. %	vein	core	rim	vein	wall rock
Al_2O_3	28.4	31.5	33.0	22.9	26.5
CaO	26.1	26.3	25.4	26.4	25.3
Fe_2O_3*	9.4	6.4	2.2	14.6	12.8

Analyst : G.R. Lachance

* Total Fe as Fe_2O_3 ; MgO and MnO are less than 0.1 per cent

Aplite-type alteration

Alteration of diabase to "aplite" was discussed in detail by Bastin (1935), who attributed all aplites to hydrothermal processes which altered the Nipissing diabase wall rocks. Various stages of so-called aplite development are shown in Figures 186 to 189. Specimen JF66-32 (Fig. 188) has pinkish feldspar borders along an arsenide vein, but the pinkish colour is restricted to feldspar in the diabase rather than being uniformly present as in a leucocratic dyke. The general absence of wall rock alteration at the outer extremities of the specimen is indicated by the preservation of orthopyroxene

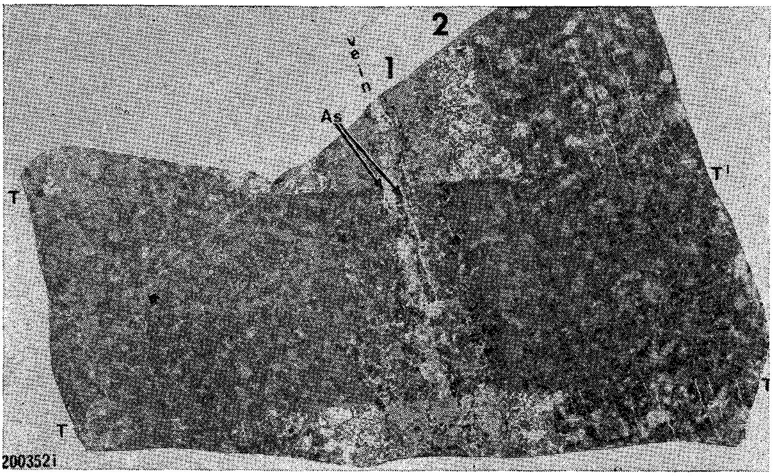


FIG. 188. Hypersthene diabase (JF66-32) from the Castle No. 2 shaft, Miller L. basin, Gowganda. The vein consists mostly of arsenides (AS) and calcite. The top and bottom of the specimen were etched with dilute HCl and stained with alizarin red ; the boundary between the etched and unetched parts of the rock is sharply defined along the top horizontal line from T to T^1, and along the bottom horizon TT. The mafic-rich zone (1) bordering the vein is pinkish in hand specimen. White spots in the etched partion of zone 2 are clinopyroxenes replaced by calcite and chlorite. Hairline fractures (far right) which parallel the vein commonly contain films of native silver. (Width of specimen approximately 15 cm).

and some inverted pigeonite. Toward the vein, sericitization increases and orthopyroxene is progressively replaced by talc pseudomorphs, and then by calcite. The clinopyroxenes remain relatively unaffected. In the mafic-poor zone (2), the principal change is the conversion of clinopyroxene to turbid pseudomorphs consisting mainly of very fine-grained calcite. In the chlorite-rich zone (1) the diabase texture has been largely destroyed because of very extensive replacement by calcite. All feldspar is albite, and the principal constituents are albite, chlorite and calcite.

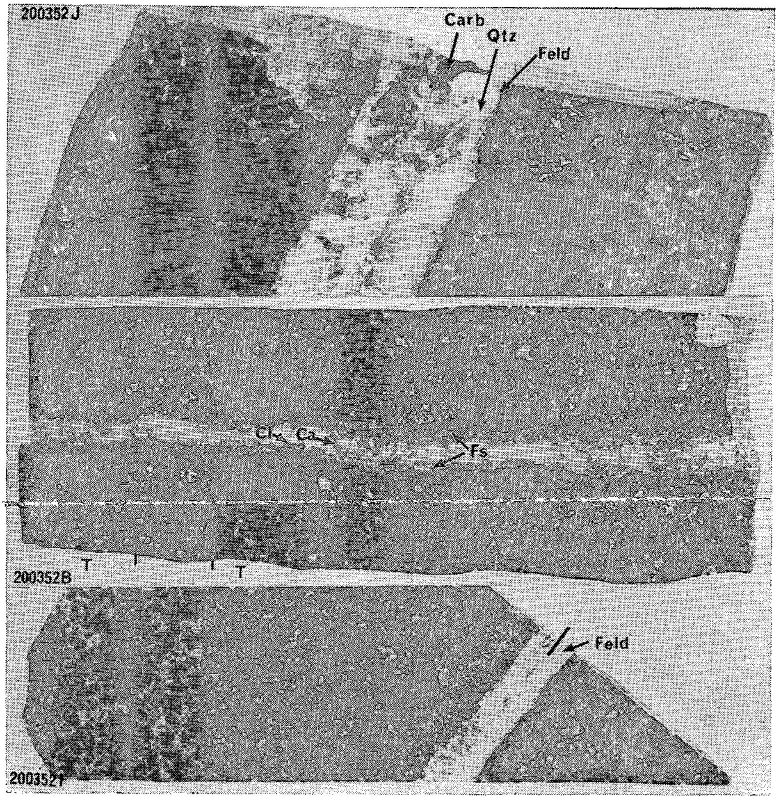
Chemical analyses of the alteration zones are given in Table 70. The increase in albitization toward the vein is evident from the progressive increase in soda. There is nothing in the texture of the altered rocks to suggest that they are not modified diabase. It is possible, however, that some albite was deposited as vein material; a few grains project into the vein calcite in the manner of crustification. The albite near the vein contains finely dispersed iron oxide, but the pinkish albite-chlorite zone is otherwise no different from equivalent zones lacking this colour.

The change from pinkish wall rock to a situation in which the colouration is exclusively restricted to the vein walls is shown in Figures 189, 190, and 191. The aplite dyke in Figure 191 has been fractured and a quartz-calcite vein asymmetrically emplaced along one wall. The contact between the wall rock and aplite is sharp (Fig. 192). Alteration in the diabase adjacent to the aplite consists of a very narrow chlorite-albite zone (averaging < 1 mm in width), followed by a broad zone of sericitization. The wall rock on the vein side of the specimen is more heavily altered, with the chlorite-albite zone extending about 6 mm from the vein. This is succeeded by a 1 mm zone in which the primary mafic minerals have been largely replaced by calcite rather than chlorite. Calcite also occurs throughout the albite-chlorite zone, but is almost absent in the wall rock bordering the aplite.

TABLE 70. PARTIAL CHEMICAL ANALYSES OF ALTERED NIPISSING DIABASE (JF66–32, FIG. 188) FROM THE CASTLE NO. 2 SHAFT, MILLER LAKE BASIN, GOWGANDA.

Wt. %	1 Pinkish	2 Light	3 "Un-altered"	ppm	1	2	3
SiO_2	34.4	39.1	47.8	Rb	NF	50	40
Al_2O_3	12.2	13.3	13.4	Sr	45	60	35
Fe_2O_3				Cr	420	300	360
FeO				Co	1200	NF	NF
NaO	0.33	0.31	0.16	Ni	220	120	140
MgO	4.0	5.7	10.5	Cu	150	270	70
CaO	17.9	16.0	9.9	Ag	<30	<30	<30
Na_2O	4.0	2.2	1.7	Zn	55	280	50
K_2O	1.1	1.7	1.7	Pb	390	1100	NF
TiO_2	0.41	0.39	0.38	As	2300	250	400
H_2O	3.3	2.9	2.0	Sb	NF	NF	NF
CO_2	12.5	8.4	1.7	Sp. Grav.	2.787	2.858	3.005
S	0.17	0.04	0.04	CaO less $CaCO_3$	2.0	5.3	7.7

Chemical analyses of the aplite and the altered wall rock on the vein side of the specimen are given in Table 71. The albite-chlorite zone (column 2) passes relatively rapidly into the sericitic zone (column 4), and hence there is some overlap in the sample from the intervening band which contains the calcite replacement of pyroxene.



FIGS. 189-191. Three samples from the Morrison property, Miller L. basin, Gowganda. In Fig. 189 a thin layer of albite (Feld) is succeeded by coarse crustified white quartz (Qtz) with a medial seam of calcite. The calcite is dark because of alizarin staining of the upper half of the specimen. (Width along the bottom is 10 cm ; JF66-114). Fig. 190 is similar, but shows relatively little alteration as indicated by the three alternating vertically-taped bands (T), of which the first two are marked. Pinkish albite (Fs) is succeeded by white crustified quartz with calcite (Ca) at the centre. Chlorite (Cl) occurs predominantly in the albite and wall rock. (Width along bottom is 20 cm; JF6-122). In Fig. 191 the vein is asymmetrical, with aplite (Feld) forming a relatively thick layer on the right side and a thin film on the left. Most of the left part of the vein consists of quartz, with a thin medial seam of calcite. Analyses of the specimen are given in Table 71. (Width along sawn base is approximately 15 cm ; JF66-115).

Worth emphasizing is the asymmetrical development of the alteration zones. The aplite seems to have had a shielding effect in that alteration is less conspicuous on the aplitic side of the specimen. Also worth emphasis is the distinctive character of the aplite; it lacks the features cited by Bastin (1935) as evidence that such material is altered diabase. Contrary criteria most readily seen in Figure 192 are the disparate grain sizes of the aplite and diabase and the absence of a mineralogical or size gradation between the two.

Alteration along actinolite veins

The presence of albite-actinolite joint fillings in the Nipissing diabase was briefly discussed in a previous paper (pp. 72-74). Alteration of the type described here is a relatively minor pre-ore feature.

Hydraulic clearing of the diabase at the Zenmac (Manridge) property, Gowganda Lake area, exposed several actinolite veins. Arsenide-bearing quartz-calcite veinlets occur within some actinolite bands, and in other cases cut across them (Fig. 193). Chemical

TABLE 71. CHEMICAL ANALYSES OF APLITE AND ALTERED DIABASE FROM THE MORRISON PROPERTY, MILLER LAKE BASIN, GOWGANDA (SPECIMEN JF66–115; FIG. 191).

	1	2	3	4	5		1	2	3	4	5
Wt. %	Pink aplite	Albite-chlorite zone	Between 2 and 4	Sericitic zone	"Unaltered"	ppm					
SiO_2	72.6	43.6	47.4	50.2	48.8	Rb	NF	NF	60	100	50
Al_2O_3	12.7	16.6	16.2	16.3	15.9	Sr	<30	<30	65	85	65
Fe_2O_3	0.7	1.8	2.1	1.1	0.9	Cr	NF	40	<30	NF	NF
FeO	0.7	11.0	7.6	6.5	7.4	Co	60	NF	NF	NF	NF
MnO	0.02	0.15	0.14	0.15	0.14	Ni	NF	80	80	80	80
MgO	1.1	7.6	7.3	6.6	6.9	Cu	170	NF	130	180	210
CaO	1.3	3.4	6.7	8.0	9.7	Ag	<30	<30	<30	<30	<30
Na_2O	6.2	4.9	2.9	2.7	2.0	Zn	160	55	70	40	55
K_2O	0.1	0.1	1.8	2.3	1.6	Pb	410	NF	NF	NF	NF
TiO_2	0.15	0.64	0.50	0.49	0.51	As	330	150	150	150	150
H_2O	0.5	5.6	4.0	2.9	2.6	Sb	NF	NF	NF	NF	NF
CO_2	0.8	2.2	1.2	0.3	0.1	Sp. Grav.	2.659	2.785	2.869	2.929	2.990
S	0.0	0.0	0.03	0.05	0.06	CaO less $CaCO_3$	0.3	0.6	5.2	7.6	9.6
Sum	96.9	97.6	97.9	97.6	96.6						

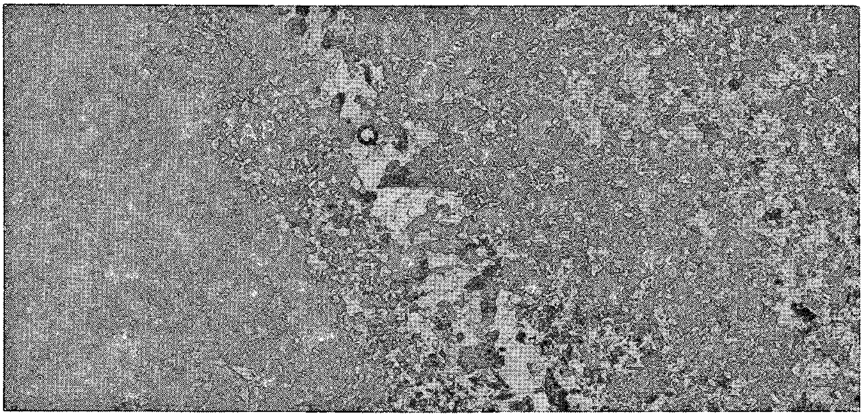


FIG. 192. Fine-grained aplite (left centre) with coarse-grained quartz-calcite vein (Q) on its right in specimen JF66-115 (Fig. 191). The wall rock to the right of the vein is darkened by alteration (thin section, transmitted light, crossed nicols).

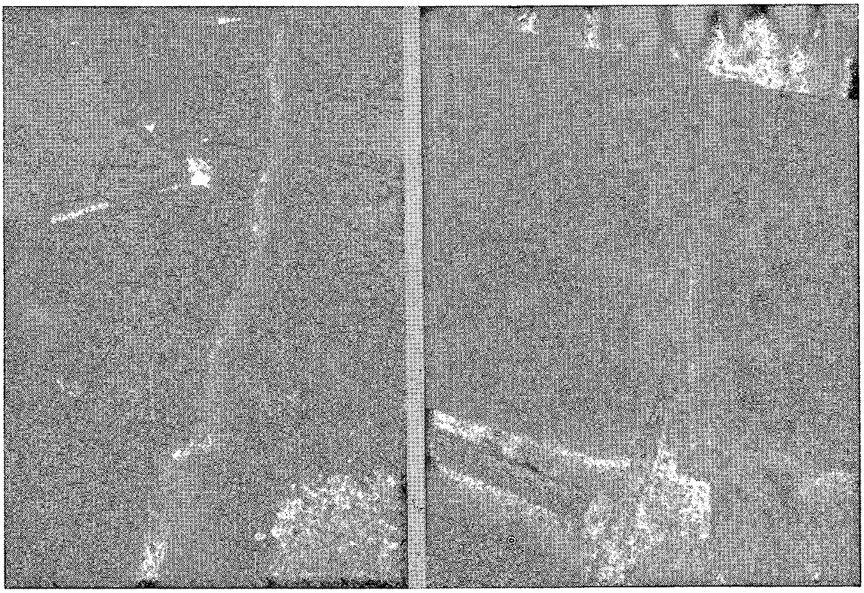


FIG. 193. Actinolite veins and associated alteration in diabase at the Zenmac property, Gowganda Lake area. The photograph on the left shows the typically composite nature of the veins, and on the right, the prominent wall rock alteration as it appears on weathered surfaces.

analyses of the alteration zones bordering one of the actinolite veins are given in Table 72. The veins consists of compact needles of actinolite, in places intergrown with quartz. Very fine, almost opaque, brown stilpnomelane is associated with the actinolite and also occurs in translucent, patchy, shred-like aggregates in the wall rock. The diabase is pinkish, both in the fresh rock and in the alteration zones. The first 3 analyses in Table 72 extend across the full width of the alteration zone. Adjacent to the vein, albite, chlorite, and stilpnomelane are the principal minerals. Much of the chlorite (one-layer polytype) is concentrated in the cores of plagioclase grains. Titanium in the analysis (column 1) is attributable to sphene aggregates averaging about 0.2 mm in diameter; some of these contain residual specks of ilmenite. Outward from the vein (columns 2 and 3), stilpnomelane decreases and becomes increasingly confined to being a replacement of the primary mafic minerals. Some calcite has a similar occurrence, but most is present in patches which have partly replaced albite. Relicts of calcic clinopyroxene are also present, and the ilmenite portions of magnetite-ilmenite intergrowths are opaque. For the "unaltered" rock (column 4), little need be said. The diabase is granophyric, and the increase in potassium marks the appearance of sericitization of the cores of the relatively soda-rich plagioclase.

TABLE 72. CHEMICAL ANALYSES OF ALTERED DIABASE FROM THE ZENMAC PROPERTY, GOWGANDA LAKE AREA. ANALYSES EXTEND OUTWARD FROM THE ACTINOLITE VEIN MARGIN (COLUMN 1) TO THE UNALTERED ROCK (COLUMN 4).

		Alteration Zone		"Unaltered"
Wt. %	1	2	3	4
SiO_2	45.9	55.0	53.9	55.7
Al_2O_3	10.5	12.9	13.2	12.6
Fe_2O_3	7.0	2.8	2.9	7.4
FeO	9.6	6.5	6.9	9.4
MnO	0.21	0.12	0.12	0.16
MgO	6.8	3.7	4.2	3.4
CaO	5.6	6.5	7.0	3.4
Na_2O	3.6	5.1	5.5	4.5
K_2O	0.4	0.4	0.3	1.1
TiO_2	2.34	2.08	2.07	1.93
H_2O	4.6	2.1	3.2	1.9
CO_2	1.4	2.6	2.3	0.3
P_2O_5	0.18	0.22	0.21	0.15
Sum	98.1	100.0	101.8	101.9

Alteration Effects on Specific Minerals

Zoned plagioclase

Plagioclase in diabase not close to ore veins is commonly altered either by saussuritization, sericitization, or a combination of these. Also typically present is the selective replacement of calcium-rich cores and the correspondingly greater preservation of the more sodic rim material.

In wall rock alteration, replacement by sericite rather than saussurite predominates. X-ray powder patterns indicate that the sericite is normal $2M_1$ muscovite. The fine-grained character of the mica makes composition determinations difficult, even with microprobe techniques. Indications are, however, that no more than 1 or 2 per cent Na_2O is present in the mineral.

The progressive replacement of calcic plagioclase by sericite and albite was described in detail by Bastin (1935). However, Scott (1964) and Dass (1970) further concluded that plagioclases progressively increase in soda toward a vein. Such a progression was also noted by Gallagher (1965) in altered basic dykes in Britain, but this trend could not be confirmed in the present study. Microprobe analyses (Table 73) support the conclusion that the change from calcic plagioclase to albitized wall rock is not transitional. A possible explanation for the results obtained by Scott and Dass is that compositions were determined optically on the more sodic unreplaced rims near the vein, but with increasing distance from the vein less alteration was present and more calcic compositions were obtainable.

Because of the complex, irregular optical character of the secondary feldspars, many of the grains were examined under the microprobe. The major concern was that K-feldspar or potassium-bearing placioclase might otherwise go undetected, especially where complex chess-board features were present. Almost all albite turned out to be relatively pure sodium feldspar (An < 5). In a few cases, however, potash-rich areas with up to 4

Table 73. Plagioclase Compositions in Diabase Wall Rock (JF66–26, Fig. 181)

Distance from vein (cm)	Alteration zone	Plagioclase composition
0	at vein wall	albite
1.4	outer edge of albite chlorite zone	albite
1.1	calcite zone, near albite-chlorite	An 70
1.2	calcite zone, near albite-chlorite	An 65–70
1.7	calcite zone, near outer edge	An 50–67
2.0	calcite zone, at edge	An 60

per cent K_2O are present. They occur in irregular patches, commonly 25 to 50 microns in diameter, which seen to be randomly distributed.

Mafic minerals

Orthopyroxene in the ordinary diabase is partly replaced by serpentine, talc, chlorite, and calcite. At the sericitized outer fringes of wall rock alteration along veins, replacement or orthopyroxene by talc is unusually common and abundant. This replacement is therefore believed to be associated with the vein alteration and, together with sericitization, is considered to be one of the first manifestations of this process.

Replacement of orthopyroxene by actinolite has not been mentioned because this phenomenon is not present in any of the specimens previously described. However, in hypersthene diabase JF69G-63, for which carbonate and chlorite analyses are given in Tables 76 and 78, actinolite pseudomorphs are present in the outer fringes of the sericitized zone. The development of these coarse, clear pseudomorphs was also recorded and discussed by Scott (1964), but as yet the documentation is insufficient to establish whether meaningful variations are present. Regardless of whether actinolite of this type is present or absent, the alteration toward the vein is similar; complete pseudomorphism of orthopyroxene, first by calcite and chlorite, and then by chlorite in the albite-chlorite zone, is the rule.

Clinopyroxene is more stable than orthopyroxene in alteration zones. In most cases clinopyroxene seems to have been relatively unaffected until the carbonate zone is reached. At this point, complete pseudomorphism by calcite and chlorite is common; however, minute relicts may persist as far as the albite-chlorite zone, where complete pseudomorphism by chlorite is the general rule.

Amphibole is less susceptible to alteration than clinopyroxene, but the effects are otherwise similar. Biotite, on the other hand, is considerably more stable and a few residual flakes have been found at the edges of veins. Usually, however, residual shreds may extend through the carbonate zone, but not through the albite-chlorite zone. One of the more interesting specimens examined for alteration effects on biotite was a lamprophyre dyke cut by an ore vein in the Silverfields mine, Cobalt. This specimen showed that biotite in the carbonate zone was partly replaced by chlorite; it is the residual biotite that was attacked by the carbonate.

Iron-titanium oxides

The effects of vein alteration on the opaque components of the diabase have been briefly mentioned, but not emphasized. Two specimens from the former Marvel Silver Mines Ltd. property in James township, northeast of Elk Lake, were chosen because of their abundant opaque constituents, and because the diabase is considerably more salic than specimens so far dealt with in this paper. In specimen JF68-224 (Table 74), grains of "iron ore" make up 3 to 4 percent of the rock. The principal mafic mineral in the unaltered rock is amphibole with small exuded magnetite grains. The main opaque constituent of the rock is, however, disseminated

TABLE 74. CHEMICAL ANALYSES OF ALTERATION ZONES IN DIABASE FROM THE MARVEL PROPERTY, ELK LAKE.*

	JF68-224			JF68-225		
Wt. %	1	2	3	1	2	3
SiO_2	61.1	54.6	54.4	62.9	57.1	58.0
Al_2O_3	13.1	13.9	13.0	12.4	13.3	13.8
Fe_2O_3	1.4	1.1	5.5	1.1	1.7	5.7
FeO	5.0	4.0	8.3	5.8	5.3	7.7
MnO	0.09	0.12	0.13	0.08	0.16	0.16
MgO	2.6	1.5	2.4	3.0	2.1	2.1
CaO	3.6	8.6	4.6	1.9	7.0	4.9
Na_2O	4.6	4.6	4.0	4.1	3.7	3.6
K_2O	1.2	1.7	1.7	0.8	1.9	2.0
TiO_2	1.73	1.58	1.56	1.81	1.70	1.71
H_2O	2.2	2.3	1.6	2.7	2.4	1.8
CO_2	2.3	6.1	1.3	1.2	4.4	0.3
P_2O_5	0.15	0.14	0.10	0.13	0.14	0.14
Sum	99.1	98.2	98.6	97.9	100.9	101.9
ppm						
Rb	<30	45	55	<30	45	70
Sr	<30	70	95	<30	85	100
Cr	200	120	120	120	100	120
Sp. Grav.	2.720	2.731	2.904	2.726	2.755	2.879
CaO less $CaCO_3$	0.7	0.8	2.9	0.4	1.4	4.5

* The zones adjacent to the veins are in column 1 and the relatively unaltered rocks farthest from the veins are in column 3.

anhedral magnetite with a grating structure of exsolved ilmenite. The veinward progression from the outer edge of the carbonate-rich zone (zone 2, Table 74) is as follows : (1) replacement of amphibole by calcite with a concomitant disappearance of the exuded magnetite. The ilmenite grating in magnetite-ilmenite intergrowths is preserved, but the encompassing magnetite has been replaced by turbid mixtures consisting principally of chlorite; (2) breakdown of the grating ilmenite into partly translucent aggregates of anatase, sphene, and relict ilmenite; (3) complete replacement of the ilmenite and grating structure. The titanium minerals present are rutile, anatase, and sphene. Also present in this zone are a few disseminated grains of pyrite and chalcopyrite. In the chlorite-rich zone (1) bordering the vein, only anatase with small amounts of sphene are detectable.

In specimen JF68-225 (Table 74), similar chemical and mineralogical variations are present. The magnetite-ilmenite intergrowths and exuded magnetite in the unaltered zone give way to ilmenite, anatase, and traces of sphene in the carbonate-rich zone. A few grains of pyrite of uncertain origin are present. At and in the albite-chlorite zone, the ilmenite grating structure is no longer preserved, but the positions and approximate grain outlines of the original magnetite-ilmenite grains are typically still recognizable. The positions are partly filled by dark brown mixtures containing anatase and sphene, but ilmenite can no longer be detected. Lozenge-shaped sphene crystals up to 0.3 mm in length are disseminated in the vein.

The above two specimens conform fairly well with titanium mineral variations found in other specimens. Although anatase occurs in some veins, sphene is more common, more abundant, and is typically coarser in grain size. In the altered zones, both anatase and sphene may be present, but anatase in general seems to be the predominant phase. Rutile is definitely a subordinate phase and usually occurs in only trace amounts. Although the mineral has been found in all altered zones, its prevalent occurrence extends from the carbonate rich band into the sericitic zone, where it coexists with ilmenite.

Individual grains of iron oxides are not present in the alteration zones of any of the specimens described in this paper. Dusty iron oxides in the feldspars are common, however, and give the albite-chlorite zone a pinkish colour in many cases. Disseminated pyrite, chalcopyrite, and rare pyrrhotite have been found in the alteration zones, but whether these formed during the early stage of wall rock alteration or were later added to the wall rock is not known. Penetration and replacement of the walls by vein arsenides is common.

Compositional variations in carbonates

It was shown in the paper on gangue minerals (p. 232) that the compositions of dolomite and calcite are highly variable. Where all the vein carbonate is calcite (as in the Miller Lake basin, Gowganda), then calcite alone is present in the wall rock. The compositions of the vein and wall rock minerals are similar, but both are variable (Tables 75 and 76). Although dolomite is the predominant gangue mineral in the Cobalt area, calcite is the predominant carbonate in most wall rocks. If dolomite had initially penetrated the wall rock and was subsequently replaced by calcite,

TABLE 75. MICROPROBE ANALYSES OF CALCITES IN HYPERSTHENE DIABASE (JF68–1300) FROM NEAR THE BOTTOM OF THE MILLER L. SHEET, SISCOE MINE, GOWGANDA.

Location	Weight %		
	MgO	MnO	FeO
in vein, at contact with wall rock	0.1	0.1	<0.1
in vein, at contact with wall	0.1	0.4	0.1
in wall rock, 9 mm from vein	0.5	0.1	0.3
3 cm from vein	0.5	0.1	0.2
9 cm from vein	0.15	0.4	0.2
11 cm from vein	0.3	0.1	0.2
12 cm from vein	0.8	0.1	0.5

Analyst: A.G. Plant

TABLE 76. MICROPROBE ANALYSES OF CALCITES IN HYPERSTHENE DIABASE (JF69G–63) FROM THE CAPITOL SHAFT, MILLER L. SHEET, HAULTAIN TOWNSHIP, GOWGANDA.

Location	Weight %		
	MgO	MnO	FeO
centre of vein	0.1	0.5	0.2
in vein, at contact with wall rock	0.4	1.8	0.9
7 mm from vein, in albite-chlorite zone	0.1	0.7	0.7
~ 15 mm from vein; pseudomorph after pyroxene	0.7	0.0	1.1
second area in above pseudomorph	0.4	0.0	0.9
~ 16 mm from vein; in another pseudomorph	0.1	<0.1	<0.1
~ 30 mm from vein; heavy sericitization	0.0	0.0	0.1

Analyst: A.G. Plant

then it might be expected that at least some residual dolomite would be present in alteration zones. This is indeed the case.

Compositional variations in chlorites

The microprobe analyses of chlorites in ore veins (p. 251) showed that the chemistry of this mineral group at Cobalt is highly variable and difficult to interpret. No systematic study of wall rock chlorites along a vein has been attempted, but a few analyses were obtained here in order to determine whether composition variations outward from a vein showed any consistent trends. Diverse chlorite compositions are present in hypersthene diabase JF66-26 (Table 64), but heterogeneity is also indicated by the presence of both I and II polytypes in the specimen.

TABLE 77. COMPOSITION VARIATIONS IN CARBONATES AND CHLORITES IN SPECIMEN JF68–35 (Fig. 194).

			Weight %	
Mineral	Location	MgO	MnO	FeO
Calcite	centre of vein	0.2	0.3	0.13
	at vein wall	0.2	1.1	0.25
	in "aplitic" rock with dolomite	2.4	0.8	0.6
	in diabase	0.2	1.0	0.7
dolomite	centre of vein	12.4	3.4	9.1
	centre of vein	18.5	1.0	2.3
	at left vein wall	12.5	3.1	8.8
	at right vein wall	12.1	2.9	9.9
	in "aplitic" rock	16.5	1.1	2.7
	intergrown with calcite (above)	18.2	1.2	2.5
chlorite	at top vein wall, IIb	14.8		25.2
		15.6		25.8
	in "aplitic" rock, IIb	18.3		25.9
		18.6		26.0
	in diabase, Ib	12.1		30.2
		12.3		30.3

Analyst: A.G. Plant

Chlorite analyses for specimen JF68-35 (Fig. 194) are given in Table 77. The vein has wide pinkish feldspathic borders which are texturally similar to the darker enclosing diabase. The features suggest that the pinkish rock is an alteration zone, and this would presumably be material of the type cited by Bastin (1935) as being indicative that all "aplites" are hydrothermally altered diabase. Chlorites in the vein and pink feldspathic alteration zone are the IIb polytype. In the darker diabase at the extremeties of the specimen, Ia and Ib ($\beta = 97°$) polytypes are present and IIb absent.

Additional chlorite analyses are given in Table 78. In specimen JF 68-1300, only the IIb polytype was found. In JF69G-63, the vein and wall rock chlorites are the Ib polytype at least as far as the sericitic zone, at which point the grains are too small for *x*-ray identifications. The results of all the analyses given indicate that no consistent compositional trends are present. In some cases the chlorites increase in iron towards a vein, but in other cases they do not.

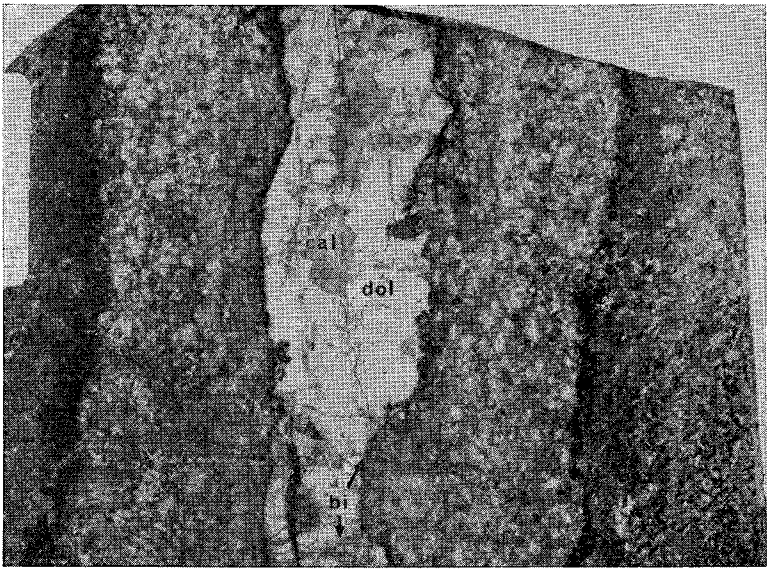


FIG. 194. A dolomite-calcite vein enclosed in pinkish feldspathic altered diabase from the Cassidy Lake area, claim C1101, Block 4, Gillies Limit township. Dolomite (dol) rhombs project into cavities filled with calcite (cal) darkened by staining with alizarin red. Thin veinlets of bismuth (bi) cut across the carbonate and darken it in places (bottom arrow). GSC Photo 301368L.

SEQUENCE OF ALTERATION

The outward progression from a vein consists of wall rock altered to (1) an albite-chlorite zone, (2) a carbonate-rich zone, (3) a sericitic zone, and thence into unaffected rock. The nomenclature of these zones is based on the presence of characteristic minerals, and is not intended to imply that others are not present or not abundant. Calcite, for example, is almost always present in the albite-chlorite zone, and chlorite is usually present in the carbonate zone. From the descriptions which have been given for the altered samples, it should also be evident that the above nomen-

TABLE 78. COMPOSITION VARIATIONS IN WALL ROCK CHLORITES.

	Specimen and Location	Weight %				
		SiO_2	Al_2O_3	MgO	MnO	FeO
P324 :	Casey township, Langis vein 37					
	in ore vein	25.8	15.3	14.9		28.1
	in ore vein	24.3	16.2	14.4	<0.1	27.7
	in wall rock, 11 mm	24.5	17.8	14.6	<0.1	27.4
	from vein (Cobalt sediment)	23.1	18.8	12.4	<0.1	27.0
JF68–1300 :	Siscoe mine, Miller L., Gowganda ; Fibrous					
	chlorite and talc at vein wall. IIb chlorite :	32.8	12.5	24.7	0.3	17.0
	6 cm from vein (in diabase)	31.4		26.4	0.30	19.1
	11 cm from vein	31.0	10.0	20.2	0.45	15.5
	12 cm from vein	29.1	11.8	21.8	0.32	16.2
JF69G–63 :	Hypersthene diabase, Capitol shaft,					
	Miller L. ; radiating sheaf at vein margin					
	a) end of sheaf projecting into vein	29.1	13.9	18.3	0.40	25.2
	b) mid-point of sheaf	25.7	15.2	12.0	0.50	32.7
	c) core of sheaf at wall rock contact	25.7	14.7	13.0	0.60	30.3
	albite-chlorite zone, 1.2 cm from vein	25.1	15.0	13.3	0.30	29.7
	carbonate zone, 1.4 cm from vein	24.2	17.9	10.3	0.30	32.2
	sericitic zone, 3 cm from vein	24.1	15.4	12.2	0.30	32.3
	in plagioclase, ~ 4.5 cm from vein	26.2	14.6	15.0	0.30	28.4
		23.8	16.9	9.8	0.30	32.1
		26.8	13.4	17.6	0.30	25.2
		26.8	13.2	19.1	0.30	23.2

Analysts : A.G. Plant and G.R. Lachance

clature is only a simplified version of the alteration assemblages which occur.

Because the symmetry of the alteration zones is so commonly bilateral, the successive alteration bands might be assumed to have formed in the sequence in which they are now present. The nature of the carbonate alteration zone was at first perplexing because many of the specimens studied had only calcite in this band. This occurred despite the fact that dolomite formed the bulk of the gangue. The sequential banding toward the vein therefore consisted of (1) sericitization (2) calcite alteration (3) an albite-chlorite zone, (4) vein dolomite, partly replaced by (5) calcite. This sequence requires an early, pre-dolomite stage of calcite formation and also fails to account for the following observations : (1) in the albite-chlorite zone bordering the veins, the indications from textural evidence are that calcite replaced the albite-chlorite assemblage. Thus, post-dolomite vein calcite spreads into the wall rock in patches and microscopic veinlets and merges with the carbonate zone of alteration ; (2) the albite-chlorite zone is gradational with the sericitic zone, but carbonate alteration is not precisely fixed in position with respect to these two ; (3) although bilateral

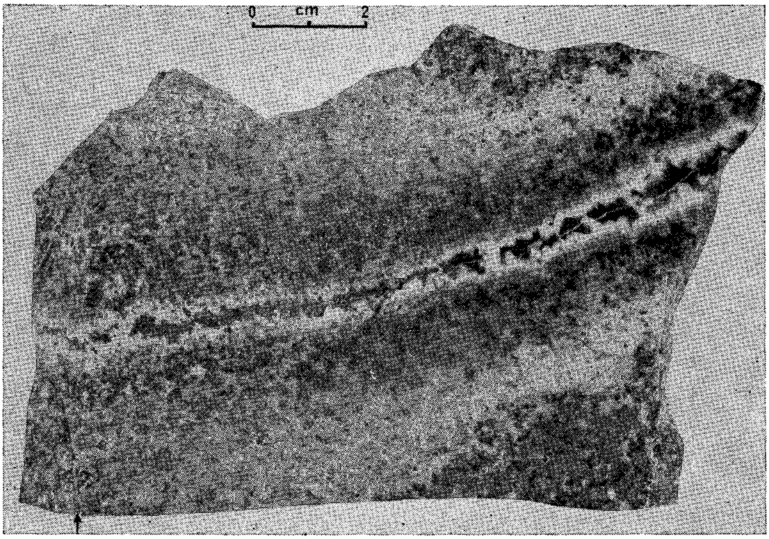


Fig. 195. Asymmetrical development of the light-coloured, carbonate-rich zone of alteration in Nipissing diabase from the Juno property, southeast of Peterson Lake, Coleman township, Cobalt. The edge of the specimen (arrow) shows that the polished surface of the specimen is normal to the veinlet containing white albite crystals projecting into dark chlorite extensively replaced by calcite. GSC 200352-A.

symmetry has been mentioned as being a characteristic feature of the alteration bands, the carbonate zone deviates from this arrangement in several cases. An example is shown in Figure 195.

On the basis of the above features and the fact that vein calcite seemed to be indistinguishable from adjacent calcite in the alteration zones, it was concluded that they were of the same origin and age. Small amounts of partly replaced dolomite were later found in the middle and outer edges of the carbonate zone in some specimens ; that is, vein and wall rock dolomite was replaced by calcite which spread through the albite-chlorite zone and most of the carbonate zone. Subsequently, dolomite veins containing a minimum of calcite were selected, and in these the carbonate alteration zone is predominantly dolomite. Thus, the evidence is that the late (*i.e.* post-dolomite) vein calcite readily penetrated the wall rock, superimposing a light-coloured, carbonate-rich zone of alteration approximately at the gradational boundary between the albite-chlorite and sericitic zones. Although partly replaced by carbonate, the albite-chlorite assemblage must be relatively stable in comparison to the more heterogeneous and initially less altered sericitic zone. The carbonate-rich milieu would therefore be less reactive with the albite-chlorite zone, thus preserving this band near the vein.

In summary, the initial alteration is believed to have been potassic, thus leading to sericitization or, alternatively, the formation of K-feldspar. Sericitic material was replaced by albite which forms part of the albite-chlorite zone bordering many veins. Everywhere there is evidence that chlorite replaced some of the albite. The final carbonate-rich alteration was superimposed on the above features. The mineralogical relationships in the alteration zones suggest that the sequence of mineral formation, from oldest to youngest was as follows : sericite (or K-feldspar), albite, chlorite, dolomite, calcite. This sequence is identical to that found for the gangue minerals of the veins.

CHEMICAL VARIATIONS

Composition-volume relationships

Gresens (1967) has derived a series of equations for quantitatively expressing the gains and losses incurred in rock alteration. The generalized equation is

$$100\left[f_v \left(\frac{gB}{gA}\right) c_n B - c_n A \right] = x_n$$

Rock *A* is altered to rock *B*, and *gA*, *gB* are their respective specific gravities. The term $c_n A$ is the weight per cent of a component (e.g. SiO_2) obtained in the chemical analysis. Because analyses are commonly totaled to 100 per cent, 100 means 100 grams, and x_n is the total amount of material (in grams) that is lost or gained in the alteration of rock A to rock B. The term f_v is the volume factor; it is the amount by which the volume of solids on the left side of the above equation is multiplied in order to obtain the volume occupied by the solids on the right side. When f_v is 1, replacement is volume for volume. When $f_v > 1$, replacement takes place with a volume gain; when $f_v < 1$, replacement takes place with a volume loss.

In order to construct a composition-volume diagram, a series of f_v values are assumed. The resultant curves for each component will cross the gain-loss zero line, and the immobile components will be clustered at one point on the line. This point is f_v; with its selection, the gain-loss equation can be solved.

Because the most significant relationship is the intersection of the curves with the gain-loss zero line, a more direct approach is to calculate the location of each component on the gain-loss zero line: $(c_nA)\ (gA)\ /\ (c_nB)\ (gB)$. This procedure gives the value of f_v at the intercept along the zero line, and the result can be plotted as a simple graph (Fig. 196). If the alteration involves both gains and losses, then the extreme end points on the graph must be components that are lost and gained. A clustering of points near the centre of the graph suggests that these are the relatively immobile components, and from this cluster an f_v value can be selected to solve the equation for the full alteration reaction. This procedure has been used for all the rock analyses accompanied by specific gravity determinations which were given in this paper. The results indicate that f_v is generally slightly greater than 1 (1.0 to 1.1), so that wall rock alteration has commonly occurred with a slight increase in volume. Exceptions to this generalization are present. SiO_2, TiO_2, MnO, and P_2O_5 are relatively immobile, and Al_2O_3 is generally the least mobile component. Substantial gains and losses in alkalis, CO_2, H_2O, and iron are the most pronounced changes in the alteration process. As an example of these changes, only specimen JF66-7a (Fig. 186) will be used. The intersections of its composition-volume equations with the gain-loss zero line are shown in Figure 196. Clustering as an indication of component immobility is fairly good, but a judgment is nevertheless needed when a specific f_v value is selected. For the albite-chlorite zone (1), silica and alumina are assumed to have been relatively immobile, and f_v is taken as being 1.04. The principal additions involved in the alteration are CO_2, H_2O, FeO, and Na_2O, whereas the greatest losses appear in S, CaO, K_2O, and Fe_2O_3. These occur with a negligible volume change ($f_v = 1$). The equation for the alteration of diabase to the albite-chlorite zone (columns 1 and 4, Table 67) is:

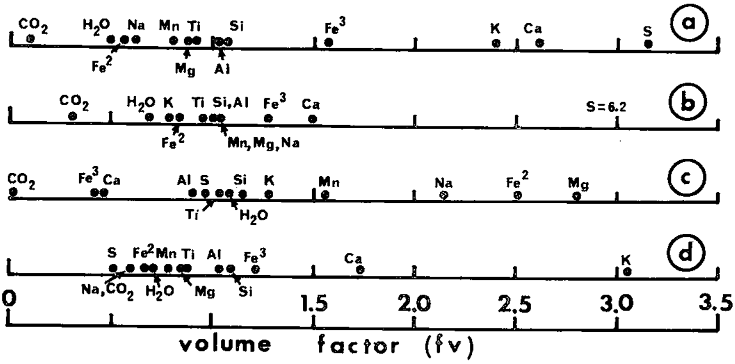


FIG. 196. Intersections of composition-volume equations with the gain-loss zero line, specimen JF66-7a; (a) the albite-chlorite zone (zones 1 and 4); (b) the sericitic zone (3 and 4); (c) the calcite-epidote zone (2 and 4); (d) alteration of the sericitic to the albite-chlorite zone (1 and 3), the process involving major losses of Ca and K.

100 grams analysis 4 + 0.17 g Al_2O_3 + 4.5 g FeO + 0.04 g MnO + 1.2 g MgO + 1.4 g Na_2O + 0.12 g TiO_2 + 2.9 g H_2O + 1.4 g CO_2 = 103 grams analysis 1 + 1.0 g SiO_2 + 0.5 g Fe_2O_3 + 6.1 g CaO + 0.9 g K_2O + 0.04 g S

Similar equations may be written to quantitatively express the gain-loss relationships for any pair of zones. Thus for zones 1 and 3 (the albite-chlorite and sericitic zones), f_v is 1.06, and the equation is:

100 grams analysis 3 + 0.6 g Al_2O_3 + 3.8 g FeO + 0.05 g MnO + 1.5 g MgO + 1.5 g Na_2O + 0.1 g TiO_2 + 1.8 g H_2O + 0.8 g CO_2 + 0.01 g S = 105 grams analysis 1 + 1.2 g SiO_2 + 0.2 g Fe_2O_3 + 2.7 g FeO + 1.4 g K_2O

Trace element variations

The trace element data in the previously-given tables of chemical analyses are based on *x*-ray spectrography of the ground, untreated analytical pulps. The distributions of most of the trace elements, such as Co, Ni, Ag, and As, indicate that the ore minerals have penetrated for variable distances into the wall rocks. High arsenic values, for example, are invariably correlative with the presence of megascopic vein-type arsenides in the wall rocks. The elements not directly involved in this type of association are rubidium, strontium, and possibly chromium.

Rubidium shows an excellent correlation with sericitization.. The abundance of the element therefore decreases toward a vein, and also toward the progressively less altered country rock. Specimens with abundant K-feldspar have a slightly different pattern only in that the maximum feldspar and rubidium abundances occur adjacent to the vein. The good correlation with both sericite and K-feldspar suggests that the altering solutions carried rubidium. In the case of strontium, several specimens show that there may be an association with calcite, but in others this correlation is not present. Strontium increases with K-feldspar toward the vein of one specimen, but in the other two the opposite trend is present. The best correlation for chromium seems to be a relationship with the albite-chlorite zone rather than with any specific element. Presumably there is an association of chromium with some of the chlorites.

FORMATION OF ALTERATION ZONES

Chlorite polytype stabilities

The relative stabilities of chlorite polytypes were discussed by Bailey & Brown (1962), Shirozu & Bailey (1965), and Bailey (1966). From theoretical considerations and from occurrences of natural specimens, the IIb layer type is the most stable structure; less stable is the Ib, and least stable is the Ia structure. This also corresponds with the decreasing order of frequency of the monoclinic polytype occurrences in the present study.

Bailey & Brown (1962) observed that Ia and Ib polytypes formed metastably in low energy, diagenetic environments, and inverted to the stable IIb polytype during metamorphism. Although the Cobalt-Gowganda veins contain both I- and II-layer polytypes, the corresponding correlation is that the I-layer types occur in the altered wall rocks more frequently than in the veins. A further correlation is that veins with massive rather than sparse or disseminated arsenides are typically accompanied by IIb polytypes. Thus the inference is that in massive arsenide veins the chlorites were raised to the appropriate higher temperature-pressure energy levels, or were initially deposited in an environment more suitable to IIb growth.

Chemical aspects of alteration

The alteration assemblages have been dealt with in terms of bulk chemical compositions as provided by the rock analyses. This treatment obscures the temporal relationships, namely, that the sericitic and albite-chlorite alteration pre-dates carbonate alteration even though they are all part of one ore-forming process. In attempting to interpret the alteration reactions as they might have occurred, it therefore seems justifiable to deal initially only with the sericite and albite-chlorite assemblages.

The depositional sequence of the pertinent gangue minerals is to have albite (or K-feldspar) followed by chlorite, and there is textural evidence of the replacement of sericitized calcic feldspar by albite. The relationships within these zones are nevertheless not sufficiently well-defined to establish whether alteration occurred sequentially or contemporaneously (see Meyer & Hemley 1967). Thus it is possible, or even probable, that the sericitic zone advanced into the unaltered rock as albitization occurred adjacent to a fissure. The fact that sericite is consistently restricted to the outermost wall rocks and does not occur adjacent to, or within the veins, is evidence that the mineral preceded or accompanied albitization, but did not post-date it. In those rocks in which K-feldspar is present at the vein margins, sericite alteration has not been found.

The abundances of the above minerals indicate that, although sodium and potassium may have been in part derived from the wall rocks, a net addition from the altering solutions has predominated. An upper temperature limit for the reactions would be of the order of 550°C, though lower temperatures (195-360°C) comparable to the fluid inclusion data of Scott & O'Connor (p. 263) seem more probable in the initial stages. Although a composition for the altering solutions cannot be specified, some qualitative aspects can be examined in terms of the mineral stability diagrams of Hemley & Jones (1964), and Helgeson (1967, 1970). Quartz is present in variable amounts in the altered wall rocks and has remained relatively stable. The albite-muscovite-K-feldspar associations suggest that, at a given temperature, $m\mathrm{Na}^+/mH^+$ and $m\mathrm{K}^+/m\mathrm{H}^+$ were both relatively high and well outside of the stability field of kaolinite. In the rocks in which K-feldspar alteration is present, muscovite is absent and pre-existing albite was consumed. In these rocks the activity ratio $\mathrm{K}^+/\mathrm{Na}^+$ was relatively high, and in rocks with the muscovite-albite alteration $\mathrm{K}^+/\mathrm{Na}^+$ was lower. Although the stability diagrams of Helgeson (1970) show the fields of albite and K-mica separated by montmorillonite, the alteration conditions in the veins of the region conform to a situation in which the intervening phase is absent.

In the development of K-feldspar alteration, K^+ is consumed ; there is no direct involvement of H^+, although indirect effects may occur because of changes in the cation $/\mathrm{H}^+$ ratios. In sericitization, however, both K^+ and H^+ are consumed and the effect is therefore to increase $\mathrm{Na}^+/\mathbf{H}^+$, that is, to shift the composition of the altering fluids toward the stability field of albite. Thus, the arrangement with albite closer to the vein indicates that $\mathrm{Na}^+/\mathrm{K}^+$ was lower in the wall rock than adjacent to the fissure. However, for any specified composition close to the intersection of the albite-muscovite-K-feldspar reaction curves, the effect of a decrease in temperature with other conditions constant would also favour the aforementioned reversal from albite toward penetration of the muscovite stability field. Thus an alternative possibility is that temperatures adjacent to the fissure were higher than in the wall rock. The succession of albite (or K-feldspar) by chlorite and epidote is not at variance with this possibility as the trend in the stability fields of these two minerals is toward enlargment as temperature increases.

Sericitization and replacement of plagioclase by the alkali feldspars releases abundant calcium from the wall rocks. Chloritization of the primary mafic minerals consumes H^+ and also releases calcium. The net effect of these reactions must therefore be to increase Ca^{++} in the altering solutions which, judging from the prevalence of dolomite and chlorite, are rich in magnesium and iron relative to alkalies at the point when the major gangue minerals are deposited. The crystallization of chlorite consumes magnesium, iron, and H^+, so that $(\mathrm{Ca}^{++}) / (\mathrm{Mg}^{++}, \mathrm{Fe}^{++})$ increases. At low concentrations of "CO_2", epidote may form, but as CO_2 activity increases the stability field of epidote is reduced (Browne & Ellis 1970). Thus the depositional sequence of chlorite → epidote → calcite may be indicative of the trend to rising CO_2 activity.

One of the most consistent and prominent features in the alteration zones of the region is the leaching of magnetite and magnetite-ilmenite intergrowths from the wall rocks. The absence of sulphurization of magnetite is a general indication that alteration was characterized by a high oxygen/sulphur fugacity ratio. On the other hand, the presence of divalent iron and manganese in the carbonates indicates that the environments of wall rock alteration and ore deposition were significantly different. Referring again to epidote, Keith *et al.* (1968) have pointed out that, in a qualitative sense, high oxygen fugacities should promote the growth of iron-rich epidote because almost all of the iron in the mineral is in the ferric state. It is appropriate, therefore, to note that the trend in epidote compositions (Table 69) is apparently toward a decrease in Fe_2O_3 prior to the cessation of crystallization of the mineral.

Where hematite is present in ore-bearing veins and occurs as discrete grains, the association is with the silicate (usually quartz) rather than the carbonate gangue. According to Petruk (p. 132), magnetite has been found in only one ore-bearing vein, and in this case the mineral occurs in carbonate at the cores of arsenide rosettes. If this is the normal trend, that is, magnetite and hematite being younger than the arsenides, then the Fe_3O_4-Fe_2O_3 stability fields (Raymahashay & Holland 1969) indicate that the onset of arsenide deposition was probably marked by a decrease in oxygen fugacity. A substantiating correlation is the presence of epidote, andradite, and chlorite in the early stages of gangue deposition and the general absence of minerals containing ferric iron in the ore-bearing stage. The early deposition of minerals containing ferric iron would have the effect of reducing the oxygen fugacity, and the crystallization of hematite or magnetite could cause it to drop drastically (though not below the stability field of these oxides). The available evidence thus indicates that the ore-bearing stage was marked by a decrease in oxygen fugacity; CO_2 and As significantly increased whereas sulphur fugacity, though higher, remained relatively suppressed in the initial stages and rose thereafter.

Concluding remarks

In a very general sense the alteration types which have been described are unrestricted in that all occur above, below, and in the Nipissing diabase. However, no vein having a large vertical and lateral extent has been examined to see whether the alteration assemblages systematically change in such a structure. Because the alteration effects are most prominently developed in diabase, and because this rock type is also the most homogeneous host for the veins, an ore-bearing structure in the sheet at Miller Lake, Gowganda, would be ideal for a study of this kind.

Wall rock alteration intersected in underground drill holes has on rare occasions been used as a basis for follow-up drilling at Cobalt, but only in areas where ore veins are known or suspected to be present. Exploration with this kind of restriction is a valid application of alteration presence, though it takes skill, as well as daring. The studies described here show that no distinction between barren and potentially productive veins can be made on the basis of the associated alteration.