Canadian Mineralogist
Vol. 23, pp. 173-186 (1985)

METAMORPHIC ASSEMBLAGES IN THE SOUTH-RANGE NORITE AND FOOTWALL MAFIC ROCKS NEAR THE KIRKWOOD MINE, SUDBURY, ONTARIO

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ABSTRACT

South-Range norite and adjacent footwall rocks of the Sudbury Igneous Complex (Ontario) have been sampled from a diamond-drill hole near the Kirkwood mine (Inco). Black norite contains hypersthene, partly replaced by cummingtonite and talc, and augite, partly replaced by actinolitic hornblende and biotite. Augite shows a reaction rim of ferroan pargasite and scapolite against plagioclase laths. Metamorphic minerals in green norite include amphiboles (actinolite, actinolitic hornblende and blue-green aluminous magnesio-hornblende), epidote, scapolite, biotite, chlorite, titanite, sodic plagioclase and recrystallized quartz. Primary igneous textures are generally preserved, but locally, and especially close to the footwall contact, quartz-rich norite is sheared and highly foliated. Green norites possess whole-rock $\delta^{18}O$ values similar to the magmatic values of the black norites, but the quartz–feldspar fractionation (4.5‰) is much larger than magmatic Δ values, in keeping with mineralogical re-equilibration under epidote-amphibolite-facies conditions. The extent of alteration of South-Range norite is consistent with progressive metamorphism from the greenschist to the amphibolite facies, with limited accessibility to the fluid phase. Footwall amphibolites are amphibole (blue-green tschermakitic hornblende with a minor green-brown hornblende core)–epidote–quartz–titanite–plagioclase rocks. This assemblage is equivalent to the metamorphic mineral assemblage of green norite. Whole-rock δ values span 1.9 to 2.9‰, indicating a lack of isotopic homogenization with the norite. However, quartz–amphibole (5.9‰) and quartz–magnetite (5.6‰) fractionations are close to those for green norite, signalling a common metamorphic event. The present study and earlier work on the Frood–Stobie-offset rocks are consistent with a post-Irruptive, probably Penokean, prograde metamorphic overprint in the Sudbury area. This event climaxed at medium-grade metamorphic conditions immediately to the south of the irruptive and faded northward.

Keywords: Sudbury Igneous Complex, Kirkwood mine, metabasite assemblages, actinolite, aluminous blue-green hornblende, Ontario.

SOMMAIRE

On a échantillonné la norite du flanc Sud et les roches encaissantes contiguës du complexe igné de Sudbury (Ontario) par un forage situé près de la mine Kirkwood (Inco). Dans la norite noire, l'hypersthène se trouve partiellement remplacée par cummingtonite + talc, et l'augite par hornblende actinolitique + biotite. En contact avec le plagioclase, l'augite montre un liseré de réaction qui consiste en pargasite ferreuse + scapolite. Dans la norite verte, l'assemblage métamorphique comporte amphiboles (actinote, hornblende actinolitique, magnésio-hornblende alumineuse bleu-vert), épidote, scapolite, biotite, chlorite, titanite, plagioclase sodique et quartz recristallisé. Les textures primaires ont survécu, en genéral, mais ci et là, particulièrement près du contact inférieur, la norite quartzifère est cisaillée et fortement foliée. La norite verte possède une valeur $\delta^{18}O$ (roche totale) semblable à la valeur magmatique de la norite noire, mais le fractionnement Δ entre quartz et feldspath (4.5‰) est beaucoup plus grand que le Δ dans une roche magmatique, ce qui indique une ré-équilibration minéralogique dans le facies amphibolite-à-épidote. Le degré d'altération de la norite du flanc Sud concorde avec un métamorphisme progressif du facies schiste-vert au facies amphibolite, où la phase fluide n'avait qu'un accès limité. Les amphibolites de l'encaissant contiennent l'assemblage amphibole (hornblende tschermakitique bleu-vert avec un petit noyau de hornblende vert-brun) - épidote - quartz - titanite - plagioclase. Cet assemblage de minéraux métamorphiques équivaut à celui de la norite verte. La valeur $\delta^{18}O$ (roche totale) va de 1.9 à 2.9 ‰, ce qui indique l'absence d'homogénéisation isotopique avec la norite. Toutefois, les valeurs Δ pour quartz–amphibole (5‰) et quartz–magnétite (5.6‰) sont proches de celles de la norite verte et témoignent ainsi d'un événement métamorphique commun. A la lumière de ces résultats et de travaux antérieurs portant sur les roches de la protrusion Frood–Stobie, on propose un épisode de métamorphisme prograde, probablement d'âge Pénokéen, en tout cas postérieur à la mise en place du complexe irruptif. Ce réchauffement a atteint son maximum, dans des conditions métamorphiques de degré intermédiaire, immédiatement au Sud du complexe, et s'est atténué en direction Nord.

(Traduit par la Rédaction)

Mots-clés: complexe igné de Sudbury, mine Kirkwood, assemblages métamorphiques de roches basiques, actinote, hornblende alumineuse bleu-vert, Ontario.

INTRODUCTION

The essential geological features of the Sudbury area are well known (*e.g.*, Card & Hutchinson 1972, Card 1978a, Naldrett *et al.* 1970), and only aspects relating to the metamorphic history will be reviewed here. Footwall rocks of the Sudbury Igneous Complex (SIC) are Archean granites and migmatites of the Superior Province to the north and east, and Early Proterozoic metasedimentary and metabasic rocks of the Huronian Supergroup to the south. Migmatites of the Superior Province are metamorphosed to the almandine-amphibolite facies, and locally to the granulite facies. This is commonly associated with the Kenoran orogeny (2.5+ Ga).

The Early Proterozoic sedimentary and volcanic rocks and the generally concordant Nipissing diabase to the south are metamorphosed to at least the low amphibolite facies in a nodal pattern (Card 1964, 1978a, b) that is very similar in style to that of the classic zonal metamorphic terrane of northern Michigan (James 1955). The latter is associated with the Penokean orogeny (about 1.9 Ga). In addition, there is some possibility that rocks of the Southern Province west of the Sudbury area were affected by a pre-Nipissing orogeny (Card 1978b).

Rocks of the North Range of the SIC are relatively unaltered, but in the East and South Ranges alteration of the norite is very extensive (Naldrett *et al.* 1970). The sedimentary and volcanic rocks of the Sudbury basin are metamorphosed to the greenschist facies (Card 1978b, Brocoum & Dalziel 1974), the grade decreasing progressively northward from upper greenschist facies in South-Range hanging-wall rocks to lower greenschist or subgreenschist facies along the northern rim of the basin (Fig. 1).

There is considerable disagreement in the literature on the timing of the post-Nipissing metamorphism and deformation event(s). Card (1978b) considered the metamorphism of the Southern Province rocks adjacent to the Irruptive to be pre-Irruptive (and Penokean) in age, and noted, in particular, that the characteristic structural elements and metamorphic mineral assemblages of these Southern Province rocks are not found in rocks of the Sudbury structure. Deformation and metamorphism of the Sudbury basin occurred in post-Irruptive times (about 1.6–1.7 Ga). In contrast, Brocoum & Dalziel (1974) argued that metamorphism of the rocks of both the Southern Province and the Sudbury structure occurred in a single (albeit protracted) post-Irruptive, Penokean orogenic event; they noted, in particular, that the penetrative foliation due to flattening is observed in both the Sudbury basin and the Southern Province.

Whereas Card (1964, 1978a, b) utilized assemblages of metamorphic minerals in the Nipissing diabase to map the metamorphic zones in the footwall rocks of the Southern Province, similar petrographic studies had not been made on rocks of the offset dykes, which are generally considered to be coeval

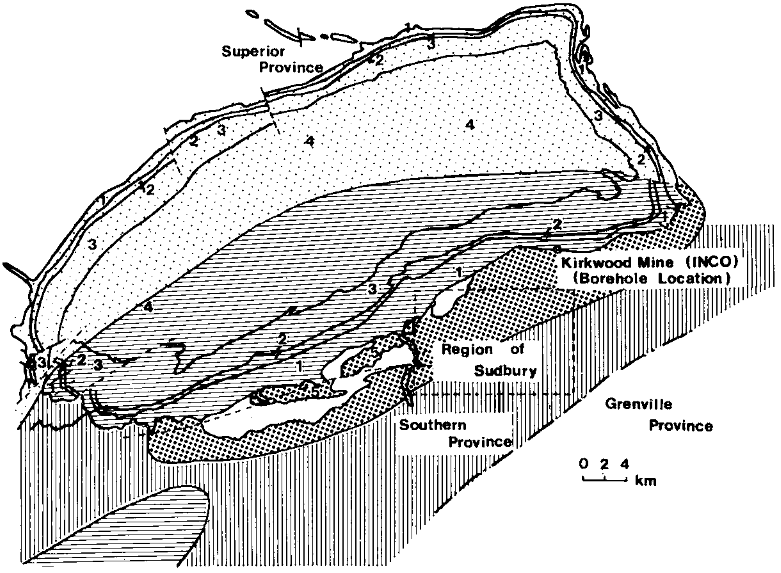

FIG. 1. Geology of the Sudbury district, with location of the Kirkwood mine and a composite of the metamorphic zones identified by Card (1978a, b), without the revision suggested by the present authors. Legend: 1 norite and quartz diorite, 2 quartz gabbro, 3 micropegmatite, 4 Whitewater Series, 5 greenstone and sedimentary rocks. Unnumbered area: granite and granite gneiss. Metamorphic facies: light stipple: subgreenschist facies, horizontal ruling: middle-greenschist facies, vertical ruling: middle- to upper-greenschist facies, heavy stipple: amphibolite facies. Geology from Inco (1980) and Card (1978b).

with the Nickel Irruptive (*e.g.*, Pattison 1979). A subsequent study (Fleet & Barnett 1978) revealed that the dominant amphibole mineral in the Frood–Stobie offset dyke, in the vicinity of the Frood mine, is a blue-green ferro-tschermakitic hornblende [since $(Na + K) > 0.6$, this is actually a ferroan pargasite on Leake's (1978) classification]. Blue-green hornblende is generally considered to be a characteristic amphibole of metabasite terranes (*e.g.*, Miyashiro 1973); it is widespread in mafic rocks of the Southern Province (Card 1964). The presence of ferroan pargasite in offset rocks establishes that the lower Proterozoic rocks in the vicinity of Frood–Stobie have been metamorphosed to at least amphibolite-facies rank in post-Irruptive times (Fleet 1980).

The present study is a detailed investigation of the petrography, mineral chemistry and oxygen isotope chemistry of samples selected from a deep drill-hole collared in footwall metavolcanic rocks near the Kirkwood mine (International Nickel Company, Inco), near Sudbury, Ontario and extending deep into the adjacent South-Range norite. This will be prefaced by a brief summary of the primary petrographic features of South-Range mafic rocks as reported by Naldrett *et al.* (1970), to avoid unnecessary repetition in the petrographic descriptions. We show that the alteration of South-Range rocks of the SIC is not deuteric (Naldrett *et al.* 1970) but metamorphic in origin. It corresponds to a prograde metamorphic overprint to epidote–amphibolite facies at the Kirkwood mine, which is consistent with the amphibolite-facies metamorphism reported for the nearby Frood–Stobie offset (Fleet & Barnett 1978, Fleet 1980).

PRIMARY PETROGRAPHIC FEATURES OF SOUTH-RANGE MAFIC ROCKS

As documented by Naldrett *et al.* (1970), the upward stratigraphic succession of South-Range igneous rocks is quartz-rich norite, South-Range norite, upper gabbro and micropegmatite. Rocks equivalent to the lower part of this succession, quartz-rich norite and most of the South-Range norite, are not exposed in the North and East Ranges of the SIC. The true thickness of the South-Range section is unknown. The horizontal thickness of the steeply inclined units of mafic rock in the two traverses investigated by Naldrett *et al.* (1970), Blezard and North Star, are about 2750 and 2450 m, respectively.

The South-Range norite is the most extensive unit. The primary rock is a medium- to coarse-grained plagioclase–hypersthene mesocumulate containing plagioclase (62%), hypersthene (20%), augite (4%), hornblende, biotite, titaniferous magnetite and quartz (8%). Hypersthene and plagioclase occur as subhedral tabular grains. Plagioclase grains have a large unzoned core and a narrow, more sodic rim. Augite occurs as anhedral grains partly molded about plagioclase and hypersthene, and quartz occurs as anhedral interstitial masses. The rock has a characteristic igneous lamination imparted by a preferred dimensional subparallel alignment of plagioclase grains.

Primary quartz-rich norite is similar mineralogically to South-Range norite, except that it contains more quartz, is slightly finer-grained and has no igneous lamination. Over a horizontal distance of 520 m to 700 m (corresponding to a true thickness 370 to 425 m), quartz increases from 8 modal % at the contact with the South-Range norite to over 20% at the footwall contact. It occurs as anhedral interstitial masses, with minor amounts of a micrographic intergrowth with feldspar. The long dimension of the plagioclase laths decreases from about 1 mm at the contact with South-Range norite to about 0.75 mm at the footwall contact.

The upper gabbro (which was not investigated in the present study) is a plagioclase–augite–ulvöspinel orthocumulate, with about 5% cumulus oxide minerals and apatite. Hypersthene is not present. The contact with the overlying micropegmatite is gradational.

The primary minerals exhibit only weak cryptic variation in composition. Plagioclase composition varies from An_{61} at the footwall contact to about An_{50} at the centre of the upper gabbro. Hypersthene composition decreases from about En_{41} at the footwall contact to about En_{31} at the contact between the quartz-rich norite and the South-Range norite and then increases slightly to En_{33} in the middle of the South-Range norite. Augite composition exhibits a similar behavior.

Apparently fresh norite appears black in hand specimen ("black" norite) owing to finely dispersed specks of iron oxide in plagioclase grains. This contrasts with altered norite, which appears green in hand specimen ("green" norite). Black norite occurs as "islands" varying from a few metres to some hundreds of metres in diameter in a "sea" of green norite. Alteration of pyroxenes is particularly severe in quartz-rich norite and over the inner third of the South-Range norite. The South-Range micropegmatite is deformed, and most samples have a pronounced foliation.

SAMPLES STUDIED

The samples for the present study were obtained from a diamond-drill hole located immediately west of the Kirkwood mine (Fig. 1). The footwall contact of the South Range of the SIC is overturned at this location, dipping 75° away from the Sudbury Basin. The drill hole is collared in footwall amphibolite. It encounters the norite contact at 1859 m and terminates at 2486 m, still within the South-Range norite (Fig. 2). Sample numbers correspond to distance in feet down the hole. Because the drill hole penetrated the SIC at the footwall contact (Fig. 2), sample numbers increase in the direction of ascending stratigraphic height.

Footwall rocks sampled are all amphibolites and evidently belong to the Elsie Mountain Formation metavolcanic suite (Elsie Mountain greenstones). South-Range SIC rocks are quartz-rich norite adjacent to the footwall contact and South-Range norite further down the drill hole. The true thickness of the quartz-rich norite zone, 116 m, is appreciably less than that observed along the Blezard and North Star traverses (Naldrett *et al.* 1970). The only "black" norite in our samples is 7050. All of the other norite samples are "green" norite.

EXPERIMENTAL

Rock samples were investigated by transmitted- and reflected-light microscopy, electron-microprobe analysis of selected mineral grains and oxygen-isotope analysis. Microprobe analytical procedures and specifications are similar to those reported in Fleet & Barnett (1978). Representative compositional data for amphiboles are reported in Table 1. The proportion of Fe^{3+} is calculated by the procedure of Papike *et al.* (1974). Amphibole classification follows Leake (1978) and Hawthorne (1983). The ratio $Mg/(Mg + Fe^{2+})$ is abbreviated in the text (below) as *mg*.

Mineral separates for oxygen-isotope analysis were prepared by standard magnetic and heavy-liquid techniques. Oxygen was extracted from minerals and powders using BrF_5 followed by quantitative conversion to CO_2, based on the methods described by Clayton & Mayeda (1963). Isotopic data are reported as $\delta^{18}O$ values in per mil relative to SMOW (Standard Mean Ocean Water). The overall reproducibility of $\delta^{18}O$ analyses is about 0.18‰ (two standard deviations). Analysis of NBS-28 gave 9.6‰.

Fractionations or differences in $\delta^{18}O$ among minerals are quoted as Δ values, defined as:

$$\Delta\ A\text{-}B = 1{,}000 \ln \alpha_{A\text{-}B} \simeq \delta_A - \delta_B$$

where $\alpha_{A\text{-}B}$ is the fractionation factor for the coexisting minerals A and B.

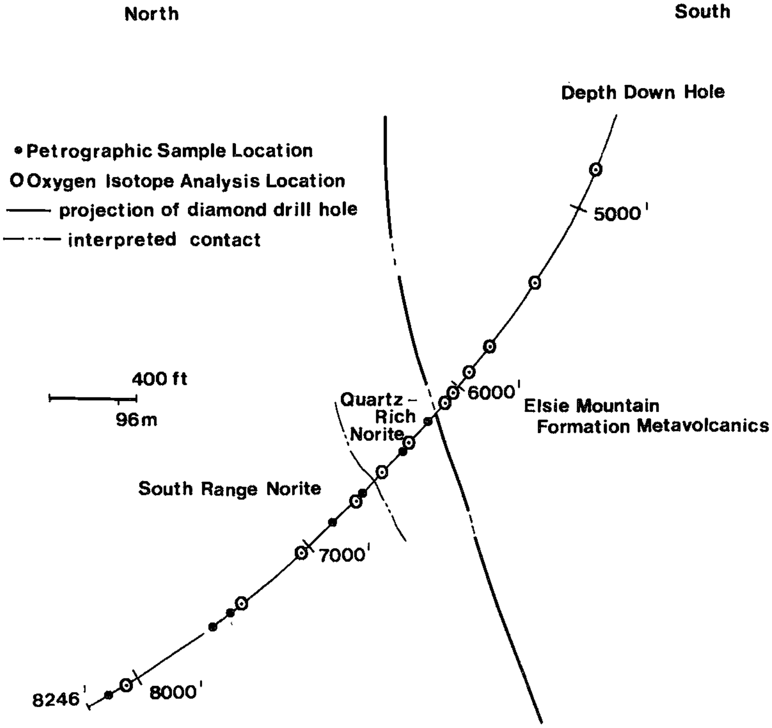

FIG. 2. Kirkwood area diamond-drill hole, with principal lithologies and sample locations. Sample numbers are derived from depth, measured in feet, courtesy of Inco.

TABLE 1. REPRESENTATIVE COMPOSITIONS OF AMPHIBOLE FROM FOOTWALL AMPHIBOLITE AND SOUTH-RANGE NORITE, KIRKWOOD, ONTARIO

ANALYSIS NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SAMPLE NUMBER	6075	4800	4800	5390	5390	5750	5750	6060	6060	6195	6195	6330	6330	6150	7050	7050	7470	7470	8155	8155
	-	CORE	RIM	CORE	RIM	CORE	RIM	CORE	RIM	CORE	RIM	CORE	RIM	RIM	_	_	CORE	RIM	CORE	RIM
SiO_2	42.93	47.33	42.51	46.38	43.37	44.76	43.82	42.15	42.89	56.05	44.07	54.71	45.03	43.75	50.88	38.23	53.17	46.04	50.30	44.36
TiO_2	0.33	1.34	0.50	1.19	0.34	1.53	0.46	2.29	0.38	0.00	0.20	0.00	0.28	0.21	0.00	0.18	0.08	0.27	0.31	0.37
Al_2O_3	13.75	7.74	12.72	8.61	12.42	9.76	13.00	11.38	14.23	0.98	14.64	1.49	13.86	15.36	5.11	15.34	4.63	13.49	5.46	12.75
Fe_2O_3*	2.24	2.71	3.07	1.00	1.65	1.93	2.43	2.23	3.50	0.62	1.74	0.47	0.30	1.12	3.72	6.46	2.52	4.92	3.60	5.11
FeO	15.32	15.61	16.00	16.90	16.87	16.09	17.43	15.59	15.10	9.04	12.85	8.79	14.11	13.25	8.40	16.22	8.04	8.88	8.53	8.59
MnO	0.29	0.43	0.23	0.32	0.27	0.25	0.30	0.31	0.33	0.10	0.17	0.17	0.27	0.24	0.16	0.00	0.25	0.27	0.24	0.18
MgO	8.64	10.40	8.19	10.12	8.48	9.78	7.93	9.02	8.06	18.27	10.45	18.04	10.11	10.07	16.42	6.98	17.38	12.57	15.90	12.50
CaO	11.55	11.20	11.81	11.97	11.86	11.81	11.57	11.76	11.61	12.79	11.91	12.45	11.89	11.50	11.05	11.70	11.93	11.55	11.77	12.01
Na_2O	1.54	0.85	1.26	1.31	1.65	1.11	1.43	1.28	1.06	0.39	1.56	0.03	1.88	2.34	0.89	1.68	0.58	1.05	0.66	1.12
K_2O	0.25	0.39	0.44	0.37	0.31	0.50	0.43	0.35	0.28	0.02	0.35	0.01	0.29	0.29	0.31	1.80	0.06	0.19	0.54	0.18
Total	96.84	98.01	96.73	98.18	97.23	97.53	98.81	96.37	97.44	98.27	97.95	96.16	98.03	98.14	96.95	98.59	98.65	99.23	97.32	97.18
Structural Formulae on the basis 23 oxygens																				
Si	6.44	7.00	6.44	6.89	6.53	6.70	6.51	6.41	6.40	7.88	6.44	7.84	6.58	6.39	7.35	5.84	7.46	6.54	7.25	6.47
Al^{IV}	1.55	0.99	1.55	1.10	1.46	1.29	1.48	1.58	1.59	0.11	1.55	0.15	1.41	1.60	0.66	2.15	0.53	1.45	0.74	1.52
Al^{VI}	0.88	0.35	0.72	0.40	0.74	0.42	0.78	0.45	0.90	0.04	0.96	0.09	0.97	1.04	0.20	0.60	0.23	0.80	0.18	0.66
Ti	0.03	0.14	0.05	0.13	0.03	0.17	0.05	0.26	0.38	0.00	0.02	0.00	0.03	0.02	0.00	0.02	0.01	0.27	0.03	0.04
Fe^{3+*}	0.25	0.30	0.35	0.11	0.18	0.21	0.27	0.25	0.39	0.06	0.19	0.05	0.03	0.12	0.40	0.74	0.26	0.52	0.39	0.56
Fe^{2+}	1.92	1.93	2.02	2.10	2.12	2.01	2.16	1.98	1.88	1.06	1.57	1.05	1.72	1.62	1.01	2.07	0.94	1.05	1.03	1.04
Mg	1.93	2.29	1.85	2.24	1.90	2.18	1.75	2.04	1.79	3.82	2.27	3.85	2.20	2.19	3.52	1.59	3.63	2.66	3.41	2.71
Mn	0.03	0.05	0.02	0.04	0.03	0.03	0.03	0.03	0.04	0.01	0.02	0.02	0.03	0.02	0.01	0.00	0.02	0.03	0.02	0.02
Na	0.44	0.24	0.37	0.37	0.48	0.32	0.41	0.37	0.30	0.10	0.44	0.01	0.53	0.66	0.24	0.49	0.15	0.28	0.18	0.31
Ca	1.85	1.77	1.91	1.90	1.91	1.89	1.84	1.91	1.85	1.92	1.86	1.91	1.86	1.80	1.70	1.91	1.79	1.75	1.81	1.87
K	0.04	0.39	0.08	0.07	0.05	0.09	0.08	0.06	0.05	0.01	0.06	0.01	0.05	0.05	0.05	0.35	0.01	0.03	0.09	0.03

* Ferric iron estimated using "midpoint" by method Papike et al. 1974.

NONMAGMATIC MINERAL ASSEMBLAGES

Footwall amphibolites

Footwall amphibolites (65–80 modal % hornblende) constitute essentially amphibole–quartz–plagioclase–clinopyroxene–titanite rocks, with sporadic chlorite, ilmenite and nickel–copper sulfides (pyrrhotite, chalcopyrite and pentlandite). Despite a significant variation in grain size and degree of crystallinity, two distinct textural-compositional varieties of amphibole are present in all samples studied. The predominant amphibole is blue-green tschermakitic hornblende (*mg* 0.50) present as coarse (3 × 1.5 mm) porphyroblastic grains, medium-sized idioblastic grains and fine acicular grains generally associated with quartz (1 in Table 1).

The second variety of amphibole in the footwall rocks is color-zoned, with a blue-green tschermakitic (*mg* 0.52) rim (3, 5, 7 and 9 in Table 1) surrounding a green-brown hornblende (*mg* 0.47) core. In some cases, the green-brown hornblende core contains fine-scale cummingtonite exsolution-lamellae and has the appearance of a relict earlier generation of amphibole. Occasionally, the core contains deformed oriented inclusions of an oxide mineral. The green-brown hornblende core is significantly enriched in Ti, which increases systematically from 1.34 through 1.53 to 2.29 wt.% TiO_2 in samples 4800, 5750 and 6060, respectively (2, 6 and 8 in Table 1).

Quartz occurs largely as patches of mosaic grains with blue-green hornblende and euhedral epidote. Plagioclase (An_{1-50}) is subordinate to quartz in all rocks except 5900. Clinozoisite is present as inclusions within quartz, as cross-cutting veins with quartz and titanite, and as dispersed grains. Titanite is present as fairly clear idioblastic to subidioblastic grains and as rims replacing earlier ilmenite (Fig. 3a).

Pyrrhotite, chalcopyrite and pentlandite occur as disseminated phases exhibiting sulfide–silicate textural relationships similar to those observed in ore of the Frood mine (Fleet 1977).

SIC norites

Minerals and mineral-alteration effects in norite of the Kirkwood core that have clearly not formed by crystal-magma processes (and which, as discussed below, we feel are metamorphic in origin) include: amphiboles, clinozoisite, scapolite, biotite, chlorite, talc, titanite, sodic plagioclase and recrystallized quartz.

By thin-section investigation, we recognize three distinct amphibole assemblages. The first consists of pale green actinolite (or blue-green actinolitic hornblende) and blue-green aluminous (and nearly tschermakitic) magnesio-hornblende. This is the common assemblage of amphibole in the "green" norite. Actinolite appears to form by pseudomorphous replacement of igneous pyroxenes, whereas blue-green hornblende appears to be a product of continued prograde reaction. Since we have not observed relict pyroxenes with this assemblage, it is not clear whether actinolite is a direct product of replacement of hypersthene or an indirect one, having formed by calcification of pre-existing cummingtonite. However, detailed comparisons of texture and mineral associations favor the former.

The precursor pyroxene (hypersthene or augite) may be readily distinguished. Grains of actinolite after augite are anhedral, subophitic to interstitial, and untwinned, except for the relict single {100} augite twins, and occasionally contain relict herringbone structure. Actinolite after hypersthene inherits the lath-like, subhedral outlines of the hypersthene grains. Moreover, it is intimately twinned, showing a complex (apparently {100}) interpenetration (Fig. 3b). Twin individuals are medium- to fine-scale in smallest dimension and appear in different section orientations as ragged lamellae, diffuse subrectangular blotches and diffuse diamond-shaped blotches. Two twin orientations are always present within the outline of each relict hypersthene grain, as required by the orthorhombic→monoclinic structural-chemical transformation.

The habit of blue-green hornblende varies from one rock to the other, apparently with progressive (metamorphic) development of the amphibole assemblage. Aluminous blue-green hornblende commonly occurs as a narrow ragged rim on actinolite after pyroxene. In other rocks, the narrow aluminous rim is still present, but the broad actinolite core is largely replaced by fine grains of blue-green actinolitic hornblende oriented parallel to the *c* axis (of the pre-existing pyroxene). With apparent continued development, a few small- to medium-scale randomly oriented grains of blue-green actinolitic hornblende appear within each outline of a pre-existing pyroxene grain, and grow progressively to medium- and coarse-scale porphyroblasts (Fig. 3c).

The second assemblage of amphiboles consists of foliated pale green actinolite (or actinolitic hornblende) and blue-green aluminous hornblende. This assemblage is developed in sheared and foliated quartz-rich norite, particularly 6195 (Fig. 3d). It occurs as ragged porphyroblasts of pale green actinolite with a blue-green hornblende rim and as ragged acicular blue-green hornblende with a restricted pale green hornblende core.

The third assemblage of amphiboles consists of cummingtonite, actinolitic hornblende and dark blue-grey ferroan pargasite. This is observed only in the black norite sample, 7050. Subhedral hypersthene is partly altered to cummingtonite and talc, leaving a core of relict hypersthene (Fig. 3e). Cummingtonite, with a *mg* of about 0.67, is in a fine-scale

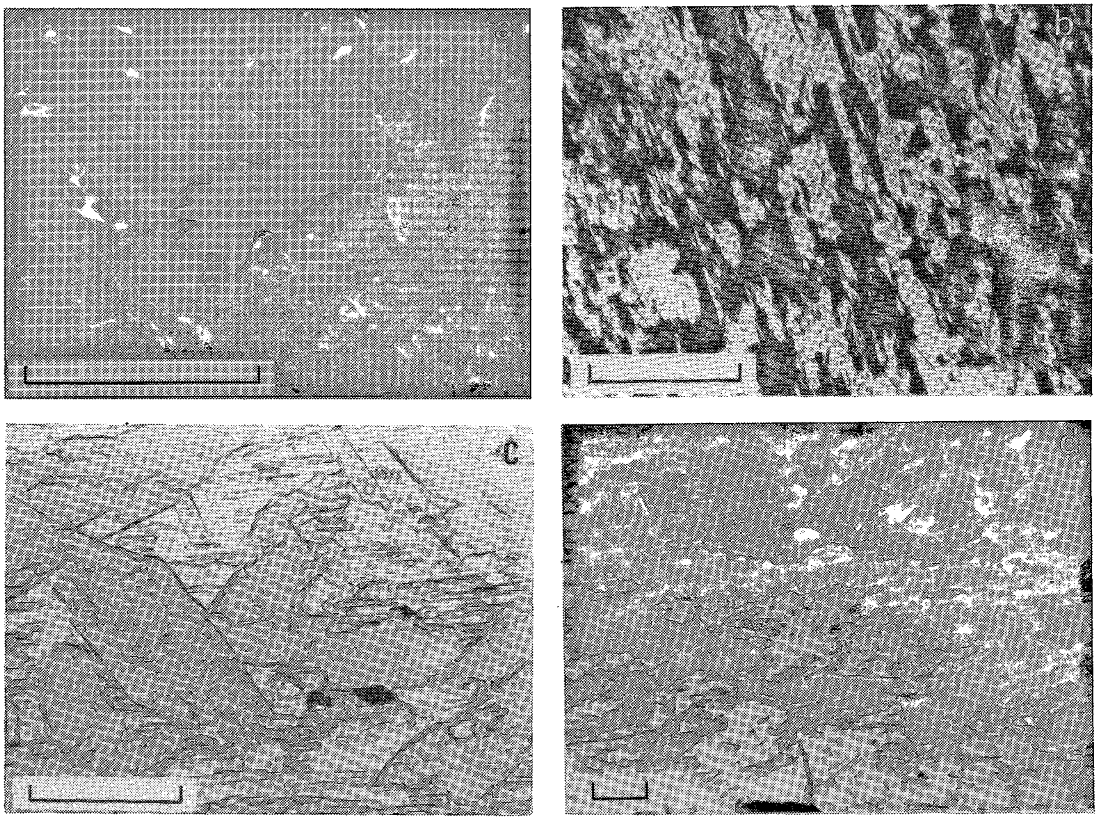

FIG. 3a-d. Textural details in Kirkwood rocks: a) titanite replacing ilmenite (reflected light, footwall, 6060); b) complex {100} interpenetration twin of actinolite after hypersthene (crossed nicols, South-Range norite, 6375); c) randomly oriented blue-green actinolitic hornblende porphyroblasts within hypersthene pseudomorph; fine, acicular blue-green actinolitic hornblende grains are parallel to hypersthene *c* axis (South-Range norite, 6600); d) foliated quartz-rich norite (amphibole has high relief; South-Range norite, 6375).

lamellar interpenetration twin. Igneous augite is largely replaced by pale green actinolitic hornblende with fine-scale cummingtonite lamellae and biotite. Patches of cummingtonite within the actinolitic hornblende may reflect original hypersthene inclusions or they may represent augite alteration. Dark blue-green ferroan pargasite occurs with scapolite as reaction rims between plagioclase and actinolitic hornblende and between plagioclase grains (Fig. 3f). Also, fine-scale ferroan pargasite *and* actinolitic hornblende grains decorate plagioclase grain-boundaries.

A second textural variety of actinolitic hornblende is present in sample 7050 as angular uniform deep green areas at the margins of augite or orthopyroxene grains that appear to have replaced pre-existing igneous hornblende. This actinolitic hornblende has the same composition as the other textural variety in 7050.

In terms of their mineral chemistry, the calcic amphiboles represent two-phase Al-poor–Al-rich assemblages (Table 1) with compositions, collectively, spanning the range from actinolite to pargasite (or tschermakite) (Fig. 4). The $Mg/(Mg + Fe^{2+})$ ratio (mg) decreases progressively with increasing Al content. Calcic amphibole compositions in the rocks analyzed may be summarized as follows: 6195: actinolite and actinolitic hornblende (mg 0.78) with aluminous magnesio-hornblende (mg 0.59). 6330: actinolite and actinolitic hornblende (mg 0.79) with aluminous magnesio-hornblende (mg 0.56). 6510: actinolitic hornblende (mg 0.76) with pargasitic hornblende (mg 0.58). 6690: actinolite (mg 0.76) with magnesio-hornblende (mg 0.65). 7050: actinolitic hornblende (mg 0.78) with ferroan pargasite (mg 0.45). 7470: actinolite and actinolitic hornblende (mg 0.79) with aluminous magnesio-hornblende (mg 0.72). 8155: actinolite ($mg = 0.70$) with aluminous magnesio-hornblende ($mg = 0.72$).

Epidote occurs throughout in amounts up to about 15 modal %. It is present along grain boundaries,

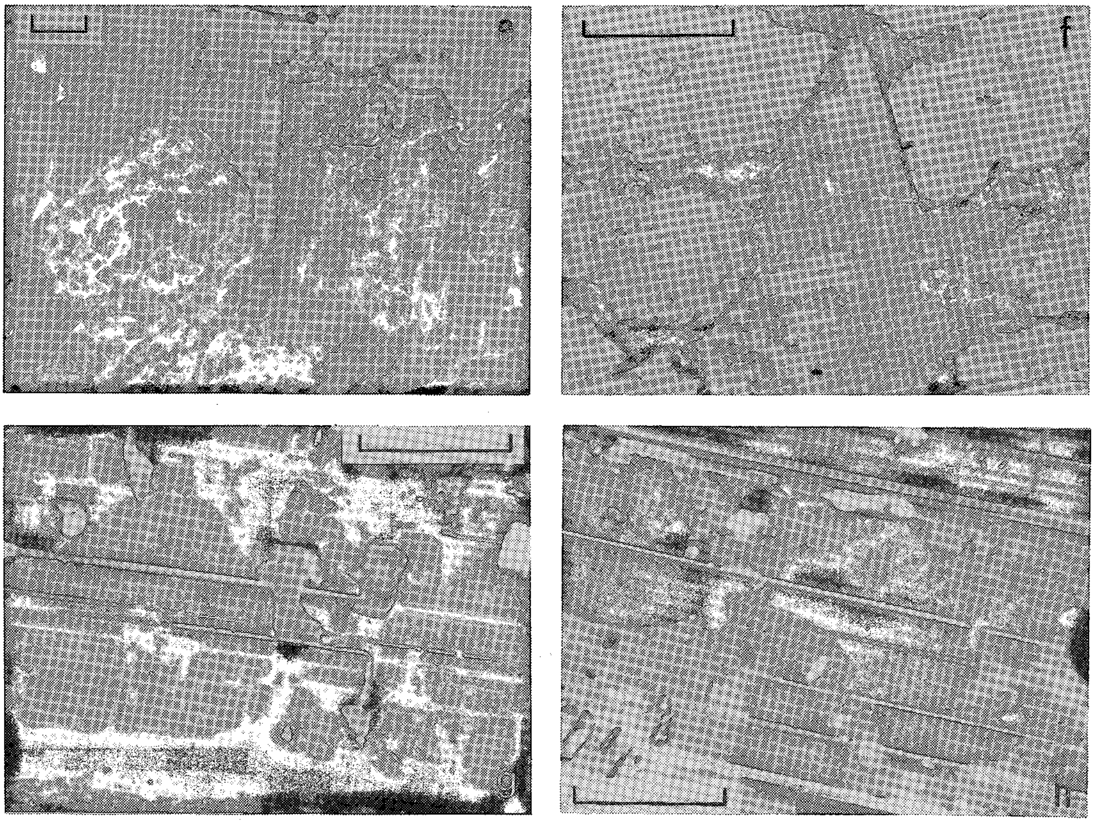

FIG. 3e-f. Textural details in Kirkwood rocks. e) hypersthene altered to talc and cummingtonite with relict hypersthene cores (South-Range norite, black norite, 7050); f) ferroan pargasite (dark) as reaction rim between actinolitic hornblende and plagioclase and between plagioclase grains (South-Range, black norite, 7050); g) scapolite patches (light grey) within irregularly zoned plagioclase (sodic, dark grey; calcic, medium grey; South-Range norite, 6510); h) irregularly zoned plagioclase (sodic, light grey; calcic, medium grey; South-Range norite, 6510). Transmitted light (except as indicated); scale bar is 0.5 mm.

particularly plagioclase–amphibole boundaries, and within grain and rock fractures.

Scapolite also occurs throughout in amounts up to about 5 modal %. It is present as subrectangular to irregular patches within plagioclase grains (Fig. 3g), at plagioclase grain-boundaries and within fractures in plagioclase grains. Scapolite, analyzed in rocks 6510, 6690 and 7050, has an average composition of about $\text{Meionite}_{42.7}$ and contains up to 2.38 wt.% Cl.

The state of preservation of primary plagioclase varies markedly from sample to sample. Compositions are summarized in Figure 5. In black norite (7050), plagioclase grains are heavily dusted with inclusions, giving the grains a brown hue in plane-polarized light, but are otherwise relatively unaltered. In green norite (*e.g.*, 6330, 6510, 6690 and 8155, Figs. 3g, h), plagioclase grains have irregular, colorless, sodic margins, which are narrow in 6690 and broad in 6330, 6510 and 8155. A broad irregular sodic margin follows grain fractures and crosses albite-twin lamellae. In the foliated quartz-rich norite, laths of original plagioclase, still recognizable in diffuse and deformed outline, are transformed to sieve-textured poikiloblasts with sutured boundaries.

Descriptions of individual norite specimens are given in the Appendix.

OXYGEN-ISOTOPE RELATIONS

The oxygen-isotope composition of whole rocks and mineral separates from the norite, along with its footwall metabasite rocks, are reported in Table 2. Whole-rock δ values for the norite are relatively uniform at 5.7 to 6.9‰, with an average of 6.4 ± 0.45‰ (1σ). No significant differences in whole-rock isotopic composition are thought to exist between the single sample (7050) of black norite (6.8‰) and its more extensively altered equivalent, the green norite.

In black norite, quartz (9.6‰), feldspar (7.6‰), pyroxene (6.8‰) and magnetite (2.2‰) are isotopically similar to their counterparts in primary mafic igneous intrusive bodies, and hence this is also the case for their mutual fractionations (*cf.* Taylor 1968). For instance, values of Δ quartz – feldspar of +2.0, and Δ feldspar–pyroxene of +0.8 are entirely in accord with the magnitude of high-temperature "magmatic" fractionations between those minerals in pristine mafic igneous rocks. Gregory & Taylor

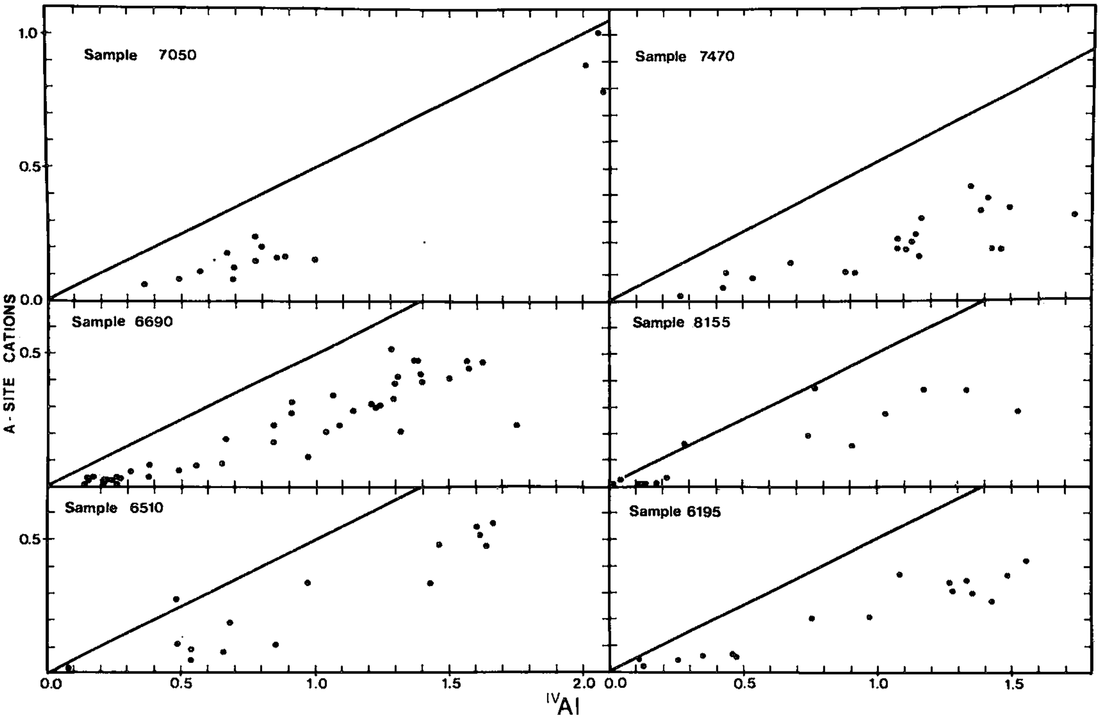

FIG. 4. Variation of total *A*-site cations with ^{IV}Al cations for calcic amphiboles at Kirkwood. Specimen 6195 is foliated quartz-rich norite, 6510 is altered quart-rich norite, 6990 is altered South-Range norite, 7050 is black norite, 7470 is deformed and altered South-Range norite, and 8155 is altered South-Range norite. Line indicates edenite substitution ($\text{Na}^{IV}\text{Al} = \square\text{Si}$) and emphasizes the high content of the tschermakite component [$(\text{Mg,Fe})\text{Si} = {}^{IV}\text{Al}{}^{VI}\text{Al}$] of the Kirkwood amphiboles.

TABLE 2. OXYGEN-ISOTOPE COMPOSITION OF WHOLE ROCKS AND MINERAL SEPARATES FROM THE SUDBURY NORITE AND FOOTWALL METABASITES AT KIRKWOOD

Sample number	$\delta^{18}O$ WR	$\delta^{18}O$ Qtz	$\delta^{18}O$ Pl	$\delta^{18}O$ Px	$\delta^{18}O$ Hbl/Act	$\delta^{18}O$ Chl	$\delta^{18}O$ Mag	Δ Qtz-Pl	Δ Pl-mafic	Δ Qtz-mafic
Footwall										
4800	2.2									
5390	1.9	9.1	6.0		2.2			+3.1	+3.8	+6.9
5750	2.3									
5900	2.7									
6060	2.8	8.8	5.8		2.9		3.2	+3.0	+2.9	+5.9
6075	2.9									
Irruptive										
6330*	6.0									
6150*	6.9	10.1	5.5		5.7	4.2	3.1	+4.6	-0.2	+4.4
6690*	6.6									
7050**	6.8	9.6	7.6	6.8			2.2	+2.0	+0.8	+2.8
7470*	6.4									
8155*	5.7	10.3	5.9		4.5			+4.4	+1.4	+5.8

WR whole rock; Qtz quartz; Pl plagioclase; Hbl hornblende; Act actinolite; Chl chlorite; Mag magnetite; Px pyroxene; mafic mafic mineral; *green norite; **black norite. Values quoted in ‰.

(1981) have shown that in primary igneous plutonic intrusive bodies of gabbroic composition, Δ quartz–clinopyroxene is between +0.5 and 1.3‰. These data are collectively interpreted in terms of retention of a primary igneous signature for black norite, a conclusion commensurate with its primary igneous mineral chemistry.

In the five samples of green norite studied, the $\delta^{18}O$ of quartz is higher by 0.6‰ and the feldspar lower by 1.9‰ relative to the black norite precursor: resultant quartz–feldspar fractionations of 4.4 to 4.6‰ are much larger than observed for primary igneous rocks, and thus definitely signify nonmagmatic conditions. Fractionations of quartz relative to amphibole and chlorite correspond, respectively, to temperatures of 440 to 550°C and 440°C, assuming isotopic equilibrium (*cf.* Javoy 1977, Wenner & Taylor 1971).

Given that quartz is relatively resistant to isotope-exchange reactions, the observed shift of +0.6‰ compared to igneous precursors in black norite signifies relatively high-temperature conditions, as

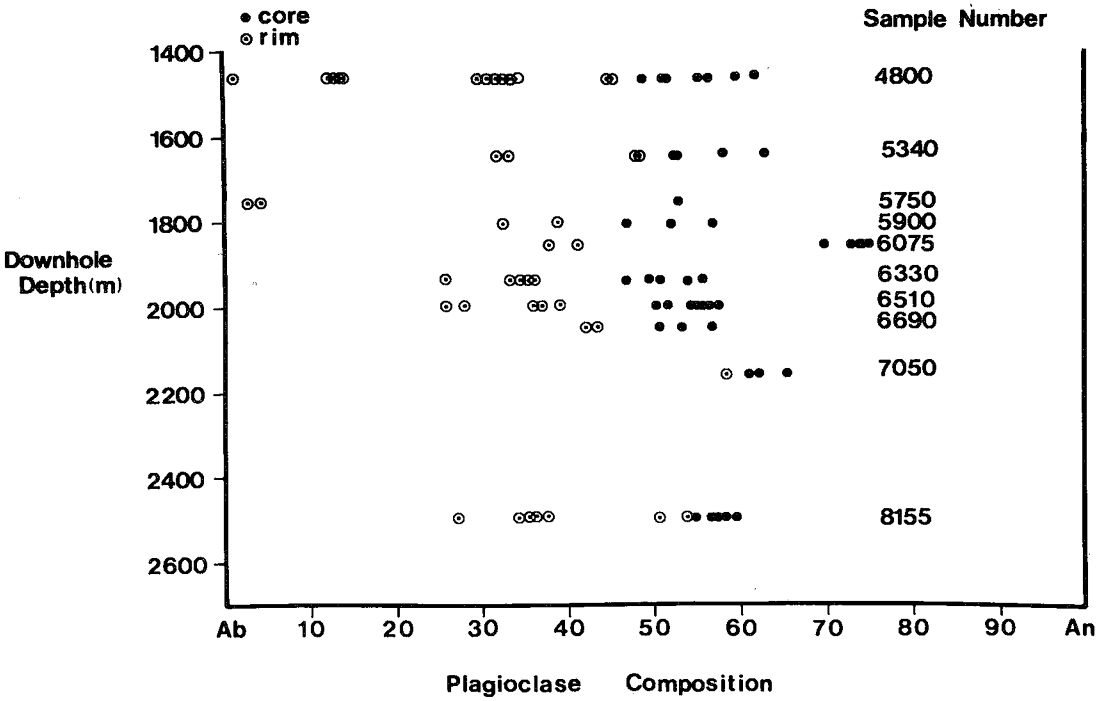

FIG. 5. Plagioclase compositions of footwall amphibolites (4800 to 6075), quartz-rich green norite (6330, 6510), South-Range green norite (6690, 8155) and South-Range black norite (7050).

independently deduced from the mineral-pair fractionations and metamorphic mineral assemblage discussed above. Based on an assumed temperature of 500°C, the calculated isotopic composition of fluids in equilibrium with quartz would be +7.5‰ (Clayton *et al.* 1972). This value is compatible with the $\delta^{18}O$ of aqueous magmatic fluids, and of aqueous fluids implicated in intermediate- to high-grade metamorphism (*cf.* Taylor 1974).

Metabasite rocks in the footwall are characterized by whole-rock $\delta^{18}O$ values spanning 1.9 to 2.9‰, indicating incomplete isotopic homogenization with the juxtaposed norite. Fresh igneous rocks of basaltic composition have whole-rock oxygen-isotope compositions of 5.5 ± 0.5‰ (Taylor 1978). The excursion to significantly depleted δ-values in footwall norites may be due to exchange with seawater at temperatures of 400–500°C during or shortly after extrusion (*cf.* Spooner *et al.* 1974, Gregory & Taylor 1981). Alternatively, the observed low-$\delta^{18}O$ values may indicate exchange with a fluid reservoir of 7.5‰ in peripheral regions of the norite at ambient temperatures of about 500°C and conditions of high water-to-rock ratio. These possibilities can be resolved only by analyzing equivalents of the footwall volcanic rocks remote from the norite.

In metabasite rocks of the footwall, quartz–amphibole (+5.9 to +6.9‰) and quartz–magnetite (+5.6‰) fractionations are close to those in the green norite, although the absolute δ values of the minerals are shifted down in the former, corresponding to the low-^{18}O whole rock. These results are interpreted to signify that the green norite and footwall metabasite rocks have retained isotopic evidence of a *shared* metamorphic event. Given the high estimated metamorphic temperatures, but resistance to isotope exchange of quartz at <300°C, the observed isotopic and mineral-exchange reactions in green norite and footwall metabasite rocks are attributed to local access by fluids, catalyzing the observed metamorphic transformations.

Isotopic differences between feldspar and amphibole are too small, or even negative (Δ -0.2 to +2.9‰) for equilibrium fractionation under metamorphic conditions. Feldspar minerals, unlike quartz, readily undergo isotope-exchange reactions down to low temperatures in the presence of a fluid phase (*cf.* Taylor 1974, 1978). Low observed δ values for feldspar are interpreted as evidence for late localized incursion of a low-^{18}O fluid reservoir such as meteoric groundwater, or formation brine of meteoric origin, into the norite and footwall metabasite rocks (*cf.* Taylor 1974, 1978). The calculated isotopic composition of fluids in equilibrium with the feldspar would be about +3‰ (300°C) to -0.5‰ (200°C) (O'Neil & Taylor 1967). It is significant that the feldspar fractions in the green norite and footwall metabasites have closely comparable δ values, such that isotopic equilibrium may have been attained for this exchangeable mineral between the intrusive body and its host rock.

BLUE-GREEN CALCIC AMPHIBOLE IN METABASITE ASSEMBLAGES

Early investigators of regional metamorphic terranes (*e.g.*, Wiseman 1934, Shido & Miyashiro 1959, Binns 1965) recognized that with progressive metamorphism, blue-green hornblende forms at the expense of actinolite. Actinolite alone is a low-grade assemblage, and aluminous (tschermakitic) blue-green calcic amphibole alone indicates the onset of medium-grade conditions (*e.g.*, Miyashiro 1973).

The first appearance of blue-green calcic amphibole varies somewhat with locality, presumably in response to local metamorphic conditions and whole-rock composition. For example, in the Aracena area, southwestern Spain, it is in the epidote–amphibolite facies (Bard 1970), in northern Michigan it is in the upper greenschist facies (James 1955) and, in the Scottish Dalradian metabasites, it coexists with actinolite throughout the chlorite, biotite and garnet zones of the associated pelitic schists (Graham 1974). However, Graham (1974) elegantly demonstrated that the blue-green hornblende of the chlorite zone is quite different in composition to that of the garnet zone. At low grade, the Dalradian hornblende is edenite-rich, whereas within the garnet zone, the hornblende is pargasitic, showing extensive tschermakite substitution.

Numerous detailed chemical petrographic and experimental studies have essentially corroborated Graham's conclusions on the paragenesis of aluminous blue-green hornblende (*e.g.*, Laird 1980, Laird & Albee 1981, Liou *et al.* 1974, Spear 1981, Moody *et al.* 1983, Apted & Liou 1983). As far as we are aware, aluminous (tschermakitic) blue-green calcic amphibole is associated with epidote–amphibolite facies or medium-grade conditions in all of the metabasite terranes investigated where independent estimates of grade have been possible. In a thorough study of interlayered pelitic and mafic schists from Vermont, Laird & Albee (1981) demonstrated that, whilst metamorphic grade may be determined readily in pelitic schists by recognition of key index minerals in hand specimen and thin section, actual mineral compositions must be known to determine the grade of a mafic schist. Thus in the present context, the mere observation that a blue-green amphibole is present is not very informative. The recent experiments of Apted & Liou (1983) on natural basalt glass show that between 500 and 550°C at 7 kbar in the presence of a Ni–NiO buffer, the Al content of calcic amphibole increases sharply from 4.5 to 12.5 wt.% Al_2O_3. Apted & Liou (1983) defined the epidote–amphibolite facies assemblages as consisting of hornblende ($Al_2O_3 > 7.8$ wt.%) + albite + epidote + quartz + titanite. This is in good agreement with field observations (*e.g.*, Laird & Albee 1981).

In the present study, the 90 or so analyses of deep blue-green hornblende rims all yielded Al_2O_3 contents in the range 10 to 14 wt.%. To be consistent with the voluminous literature on this topic, these compositions cannot be associated with mid-greenschist facies conditions, as Figure 1 suggests. They must be assigned to at least the transitional greenschist–amphibolite facies if not the epidote-amphibolite facies.

Finally, the composition of the aluminous blue-green calcic amphibole from the Frood–Stobie offset is remarkably similar to that of the classic blue-green hornblende from the Dalradian garnet-zone amphibolites (Table 3). Ferroan pargasite is the dominant amphibole in both of samples 424 and 18229. It occurs as porphyroblasts in 424 and as poikiloblasts in 18229. Neither rock contains epidote. Thus, the Frood–Stobie offset has been metamorphosed to amphibolite-facies conditions.

DISCUSSION

It is well known that the extent of metamorphism of mafic rocks to the amphibolite facies at low and moderate load-pressures is critically dependent on the availability of fluids (*e.g.*, Winkler 1974, Miyashiro 1973). Thus, metabasites derived from permeable pyroclastic rocks are more easily recrystallized and show more marked schistosity and more complex variation in composition than those derived from less permeable lavas and small intrusive bodies. Primary textures may be preserved in coarse-grained mafic rocks. Winkler (1974) noted that metamorphic reactions are inhibited in impermeable mafic rocks and cited the unchanged *inner* part of gabbro plutons in metamorphic terranes.

The recent study of Kline (1984) on the Doré Lake Complex within the Matagami–Chibougamau greenstone belt nicely illustrates the effects of limited availability of fluid during metamorphism. Surrounding metabasalts have typical greenschist assemblages, and indicate a low-pressure (Abukuma) type of metamorphism. However, metamorphism of the layered intrusive complex is incomplete. A number of relatively unmetamorphosed rocks occur, preserving primary plagioclase and, less commonly, clinopyroxene and orthopyroxene. Even in more metamorphosed rocks, plagioclase is commonly primary in appearance, and its failure to extensively react inhibits the formation of aluminous calcic amphibole. Clinopyroxene is commonly pseudomorphically replaced by ferroactinolite or ferro-pargasite or both, and orthopyroxene is pseudomorphically replaced by cummingtonite or grunerite.

TABLE 3. COMPARISON OF ALUMINOUS BLUE-GREEN HORNBLENDE FROM FROOD-STOBIE OFFSET AND DALRADIAN GARNET-ZONE AMPHIBOLITE

	ferroan pargasite, Frood-Stobie[1]		pargasitic hornblende, Dalradian garnet zone[2]	
	424	18229	25008	25099
SiO_2	40.7	41.4	40.8	43.3
TiO_2	0.4	0.4	0.4	0.5
Al_2O_3	15.2	15.4	14.5	14.2
Cr_2O_3	0.1	0.2	-	-
FeO*	22.0	20.1	23.8	21.4
MnO	0.3	0.3	0.3	0.2
MgO	5.5	6.6	5.1	5.7
CaO	11.4	11.5	10.8	9.1
Na_2O	1.7	1.6	2.0	2.5
K_2O	0.5	0.5	0.8	0.7
	97.8	98.0	98.5	97.6

1 Fleet & Barnett (1978, Table 1). 2 Graham (1974, Table 2).
* Total iron expressed as FeO.

The nonmagmatic minerals in South-Range mafic rocks at Kirkwood described above (actinolite and actinolitic hornblende, epidote, chlorite, titanite, recrystallized quartz, biotite, aluminous blue-green hornblende, pargasite and cummingtonite) are typical of the upper-greenschist- to low-amphibolite-facies assemblages in metabasites (*e.g.*, Miyashiro 1973). Talc, scapolite and a sodic plagioclase rim are also consistent with metamorphism to these conditions. The limited reaction of the primary plagioclase, preservation of primary textures in undeformed rocks, reactions involving intergranular minerals, the patchy (or blocky) distribution of black norite within green norite, and localized shearing are all consistent with restricted access of fluid during metamorphism.

The degree of preservation of recognizable igneous textures and minerals and their conversion to metamorphic assemblages and textures are considered to directly reflect accessibility of fluid during progressive metamorphism from the greenschist to the amphibolite facies. It is therefore important to recognize that varying assemblages may result although the same temperature of metamorphism is maintained. This is well illustrated in sample 7050, which has interacted only to a minor extent with the greenschist metamorphic fluids, as evidenced by abundant relict orthopyroxene and minor augite. Unlike the remainder of the South-Range samples examined, where aluminous blue-green hornblende rims actinolite, and sodic plagioclase replaces more calcic plagioclase, ferro-pargasite and scapolite are noted at mutual grain-boundaries and within single grains of plagioclase cross-cutting polysynthetic twinning. Pale brown iron-rich calcic plagioclase away from scapolite – ferro-pargasite veinlets grades into iron-poor sodic plagioclase at veintlet margins, indicating a release of Ca, Al and Fe^{3+} to solutions. An appreciable Cl content of the invading fluids is indicated by the uniformly elevated Cl content of scapolite. The unique and peculiar P–T fluid regime prevalent during this reaction is supported by the textural observation that scapolite and blue-green ferroan pargasite consistently occur at mutual plagioclase grain-boundaries or within single plagioclase grains, yet do *not* occur in contact with altered pyroxenes. These relationships are interpreted to represent the case where the attendant metamorphic fluids are so minor in volume that they are dominated by the rock chemistry.

Only with progressive ingress of fluid, possibly under conditions of increasing temperature, did the igneous ferromagnesian phases in the South Range of the SIC become involved in hydration reactions resulting in the conversion of high-temperature igneous phases to amphiboles. The inference from the consistently present low-Al core regions is that the earliest replacement of pyroxene was initiated by a low-temperature greenschist-facies fluid that selectively replaced pyroxenes without significantly involving the adjacent plagioclase. With increasing temperature and participation of plagioclase in fluid-dominated reactions of increasing metabasic character, a reaction rim of aluminous blue-green hornblende developed and progressively consumed the low-aluminum actinolite pseudomorphs of pyroxene.

The stability of blue-green hornblende in the most advanced stages of the fluid-dominated reactions is indicated in the amphibole-rich shear zone observed in sample 6195. The presence of a pale green low-aluminum core (number 10 in Table 1) in highly foliated amphibole grains in this sample is good evidence that the existence of this shear zone actually spanned the period of the greenschist- to amphibolite-facies transition to affect the South-Range norite and subjacent footwall rocks in the vicinity of Kirkwood. Perhaps narrow shear-zones such as these permitted accessibility of low-temperature fluid, resulting in pervasive conversion of pyroxenes to low-aluminum tremolite–actinolite pseudomorphs.

Therefore, we consider the alteration of South-Range rocks to be the result of a metamorphic overprint. We appreciate that superficially these rocks may appear to be unmetamorphosed. However, for petrologists who feel that the mineral assemblages we have described are not uniquely characteristic of metamorphism but may also be formed by deuteric processes, we point to the existence of similar assemblages in foliated and largely recrystallized norite, of incipient deformation in many specimens of green norite, and of compositionally equivalent mineral assemblages in the adjacent Elsie Mountain footwall rocks. Although the supporting oxygen-isotope data are consistent with either a local hydrothermal metamorphism or a regional metamorphic overprint, we emphasize that the prograde nature of the South-Range metamorphism (aluminous blue-green amphibole after actinolite, *etc.*) appears to exclude the possibility of hydrothermal metamorphism related to the emplacement of the SIC. Furthermore, since the metamorphism is associated with some deformation, it most logically occurred during deformation of the Sudbury structure. The lack of albite–oligoclase plagioclase (Fig. 5) appears to suggest a low or moderate pressure but, in view of the limited reaction of the primary plagioclase, this criterion could be quite ambiguous.

The green-brown hornblende core in zoned amphibole grains of the footwall amphibolites may be relict from a previous metamorphic event at a somewhat higher grade. The Ti content of the core is consistent with upper-amphibolite-facies conditions (Raase 1974). Alternatively, the general trend to increasing Ti-content with proximity to the contact of the SIC might provide evidence for the existence of a contact aureole that logically should be present at the margin of a mafic intrusive mass of this magnitude. Whatever the origin of this earlier metamorphic event, the blue-green tschermakitic rim surrounding the Ti-rich core clearly indicates that the mafic rocks in the footwall of the SIC have been subjected to a second metamorphic event at a slightly lower grade.

The present study on SIC and footwall rocks at Kirkwood and that of Fleet & Barnett (1978) on Frood–Stobie offset rocks are consistent with a post-Irruptive, probably Penokean, prograde metamorphic overprint in the Sudbury area. This appears to have climaxed at medium-grade conditions immediately to the south of the SIC and faded northward. The regional extent of this metamorphism and its relationship to the metamorphism mapped by Card (1978a, b, Fig. 1) are presently under study.

ACKNOWLEDGEMENTS

We thank the International Nickel Company (Inco) for provision of samples for study. The first author is particularly grateful to Inco staff members for lengthy discussions regarding Sudbury geology. We express thanks to Lynn Willmore for skillful assistance with mineral separations. An earlier manuscript version was improved by reviewers K.D. Card and H.P. Taylor Jr. and by editorial assistance. This study was supported by Natural Sciences and Engineering Research Council of Canada operating grants to M.E. Fleet and R. Kerrich.

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Received May 9, 1984, revised manuscript accepted December 21, 1984.

APPENDIX I. PETROGRAPHIC FEATURES OF INDIVIDUAL SAMPLES OF NORITE

6195. Foliated quartz-rich norite (green norite). This rock is strongly foliated into "dark" bands of blue-green hornblende mantling pale green actinolitic hornblende, chlorite and biotite (*e.g.*, Fig. 3d) and "light" bands of quartz, plagioclase, epidote and chlorite. Large areas of the original rock have been more-or-less totally recrystallized. Laths of original plagioclase are now sieve-textured poikiloblasts with sutured boundaries. The sieve texturing appears to involve sodic plagioclase in calcic plagioclase. In more highly sheared areas of the thin sections examined, the plagioclase is reduced to small recrystallized grains in the quartz-plagioclase-epidote groundmass.

6330. Altered quartz-rich norite (green norite). The amphibole assemblage is actinolite after pyroxenes (and possibly primary hornblende) rimmed by blue-green hornblende. Many amphibole areas are poikiloblastic or otherwise incipiently deformed, and the grain margins are sutured and fragmented into fine-scale blue-green amphibole. Plagioclase is superficially unaltered, but closer examination reveals that it is dusted with iron oxide and contains numerous inclusions of idioblastic acicular blue-green amphibole. Interstitial quartz is recrystallized and develops sutured boundaries against plagioclase grains. Fractures in plagioclase are decorated with sheared biotite, epidote and chlorite.

6375. Altered and partly sheared South-Range norite (green norite). Over most of the thin section examined, alteration of the primary mineralogy is similar to that of 6330, with rather more sheared biotite, epidote, chlorite, scapolite and titanite. However, one corner of the section is sheared and foliated in the manner of 6195 (Fig. 3d). The amphibole assemblage remains actinolite and blue-green amphibole in the sheared area.

6510. Altered quartz-rich norite (green norite). Similar to 6330 except that the amphibole areas are much more poikiloblastic; biotite, scapolite (about 5 modal %) and titanite are more abundant. Also, the primary plagioclase grains have extensively reacted to broad, irregular margins of more sodic plagioclase (An_{25-30}, Figs. 3g,h) leaving irregularly shaped relict islands of calcic plagioclase. Relict albite twin-lamellae are continuous through both calcic and sodic regions.

6600. Altered South-Range norite (green norite). Blue-green actinolitic hornblende is largely recrystallized to irregularly oriented medium-scale porphyroblasts within grain outlines of primary pyroxene. Biotite, chlorite, epidote and scapolite are relatively abundant. Plagioclase and quartz alteration are similar to that of 6330.

6650. Extensively altered South-Range norite (green norite). The amphibole assemblage is actinolite plus blue-green hornblende as in 6330. About half of the original plagioclase is replaced by epidote and scapolite. Chlorite is abundant.

6690. Altered South-Range norite (green norite). The amphibole assemblage is poikiloblastic actinolite + blue-green hornblende. The thin section examined is transected by a sheared vein of epidote, mosaic quartz and titanite. There is up to 10 modal % scapolite, abundant epidote and chlorite. Plagioclase grains have a thin sodic margin and contain inclusions as in 6330.

6830. Altered South-Range norite (green norite). Similar to 6375.

7050. Weakly altered South-Range norite (black norite). Subhedral hypersthene partly replaced by cummingtonite and talc, and augite partly replaced by actinolitic hornblende and biotite, as described above. Primary plagioclase grains are heavily dusted with iron oxides and acicular hornblende. The rock also contains ferroan pargasite and scapolite.

7140. Altered South-Range norite (green norite). Earlier actinolite largely replaced by irregularly oriented idioblastic blue-green hornblende. The rock contains about 10% scapolite, chlorite, minor epidote.

7470. Deformed and altered South-Range norite (green norite). Blue-green hornblende poikiloblasts are deformed in wavy foliated bands. Plagioclase grains are irregularly zoned to a more sodic margin. About 5% scapolite replaces plagioclase.

7565, 8065, 8155. Moderately deformed and altered South-Range norite (green norite). Large grains of actinolite after pyroxene with larger twin-domains than in previously described specimens. The actinolite tends to be poikiloblastic and with a broad rim of blue-green hornblende. Plagioclase grains exhibit cataclastic deformation, with fractures filled with chlorite, biotite, quartz and epidote; these grains have a broad irregular sodic margin. Scapolite and titanite are also present.