Canadian Mineralogist
Vol. 25, pp. 499-514 (1987)

PROGRADE METAMORPHISM OF THE SUDBURY IGNEOUS COMPLEX

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ABSTRACT

Systematic study of the Sudbury Igneous Complex (SIC) indicates a low-pressure (or low- to medium-pressure) prograde metamorphic overprint that climaxed at medium-grade conditions immediately to the south of the Irruptive and faded northward. Metabasite assemblages of the South Range and adjacent offsets are consistent with a zonal pattern of metamorphism equivalent to that of adjacent and enclosing Southern Province rocks. Thus the zonal Southern Province metamorphism is established as post-Irruptive and probably Penokean in age. The composition of calcic amphibole is the most important indicator of metamorphic grade in the SIC. The onset of middle- and upper-greenschist facies is marked by the appearance of actinolite and the disequilibrium assemblage actinolite + actinolitic hornblende ± hornblende - edenite. The epidote–amphibolite facies is characterized by either coexisting actinolitic hornblende and tschermakitic hornblende or blue-green hornblende alone. The low-amphibolite facies is characterized by either dark blue-green tschermakitic hornblende or dark blue-green ferroan paragasite ± cummingtonite; epidote and actinolite are essentially absent, and almandine garnet is present only in the more fractionated quartz diorite compositions.

Keywords: Sudbury Igneous Complex, Ontario, prograde metamorphism, metabasite assemblages, calcic amphiboles.

SOMMAIRE

Une étude systématique du complexe igné de Sudbury indique la superposition d'un événement prograde à basse pression (ou à pression de basse à moyenne). Cet événement a atteint son point culminant (à un degré de métamorphisme moyen) immédiatement au sud du complexe; son influence a diminué vers le nord. Les assemblages des métabasites du flanc sud du complexe et des décrochements voisins concordent avec la zonation dans le degré de métamorphisme des roches encaissantes de la Province du Sud. On établit donc que cet événement est postérieur à la mise en place du complexe, et probablement d'âge pénokéen. La composition de l'amphibole calcique constitue l'indicateur le plus fiable du degré de métamorphisme. L'amorce du facies schistes-verts moyen et supérieur se voit par la formation de l'actinote et de l'assemblage en déséquilibre actinote + hornblende actinolitique ± hornblende ou édenite. Le facies amphibolite à épidote est marqué soit par la coexistence de hornblende actinolitique et hornblende tschermakitique, soit par la présence de hornblende bleu-vert seule. Les métabasites dans le facies amphibolite inférieur contiennent hornblende tschermakitique bleu-vert foncé ou pargasite ferreuse bleu-vert foncé ± cummingtonite; épidote et actinote sont absentes à toutes fins pratiques, et un grenat proche du pôle almandin caractérise les compositions plus fractionnées (diorite quartzifère).

(Traduit par la Rédaction)

Mots-clés: complexe igné de Sudbury, métamorphisme prograde, assemblages de métabasites, amphiboles calciques, Ontario.

INTRODUCTION

The extensive alteration of the noritic rocks of the East and South Ranges of the Sudbury Igneous Complex (SIC, Fig. 1) is usually attributed to deuteric alteration (*e.g.*, Naldrett *et al.* 1970) and not to a regional metamorphic overprint. The quartz diorite host-rock at the Frood mine has been metamorphosed to amphibolite-facies conditions (Fleet & Barnett 1978). Thomson *et al.*(1985) documented a transitional greenschist–amphibolite facies overprint in the South Range at Kirkwood. Also, Dressler (1984a) noted that the South Range has been affected by a strong regional metamorphic overprint. The present paper extends these findings, and documents a prograde regional metamorphic overprint to the Sudbury Igneous Complex through comprehensive study of the associated metabasite assemblages.

Footwall rocks are Archean granites and migmatites of the Superior Province to the north and east, and Early Proterozoic metasedimentary and metabasite rocks of the Huronian Supergroup to the south. Migmatites of the Superior Province have been metamorphosed to the almandine-amphibolite facies, and locally to the granulite facies (the Levack Gneiss Complex, Dressler 1984b), and are probably late Archean in age (Card *et al.* 1984). The Early Proterozoic sedimentary and volcanic rocks and the generally concordant Nipissing diabase to the south have been metamorphosed to at least the low-amphibolite facies in a localized zonal (nodal) pattern (Card 1964, 1978a, b). This metamorphism of the Southern Province occurred in the Middle Proterozoic, probably during the Penokean orogeny (James 1955, Cannon 1973). Contact-metamorphic features due to the emplacement of the Irruptive are preserved in the North Range footwall but have been all but obliterated in the South Range footwall (Dressler 1984a).

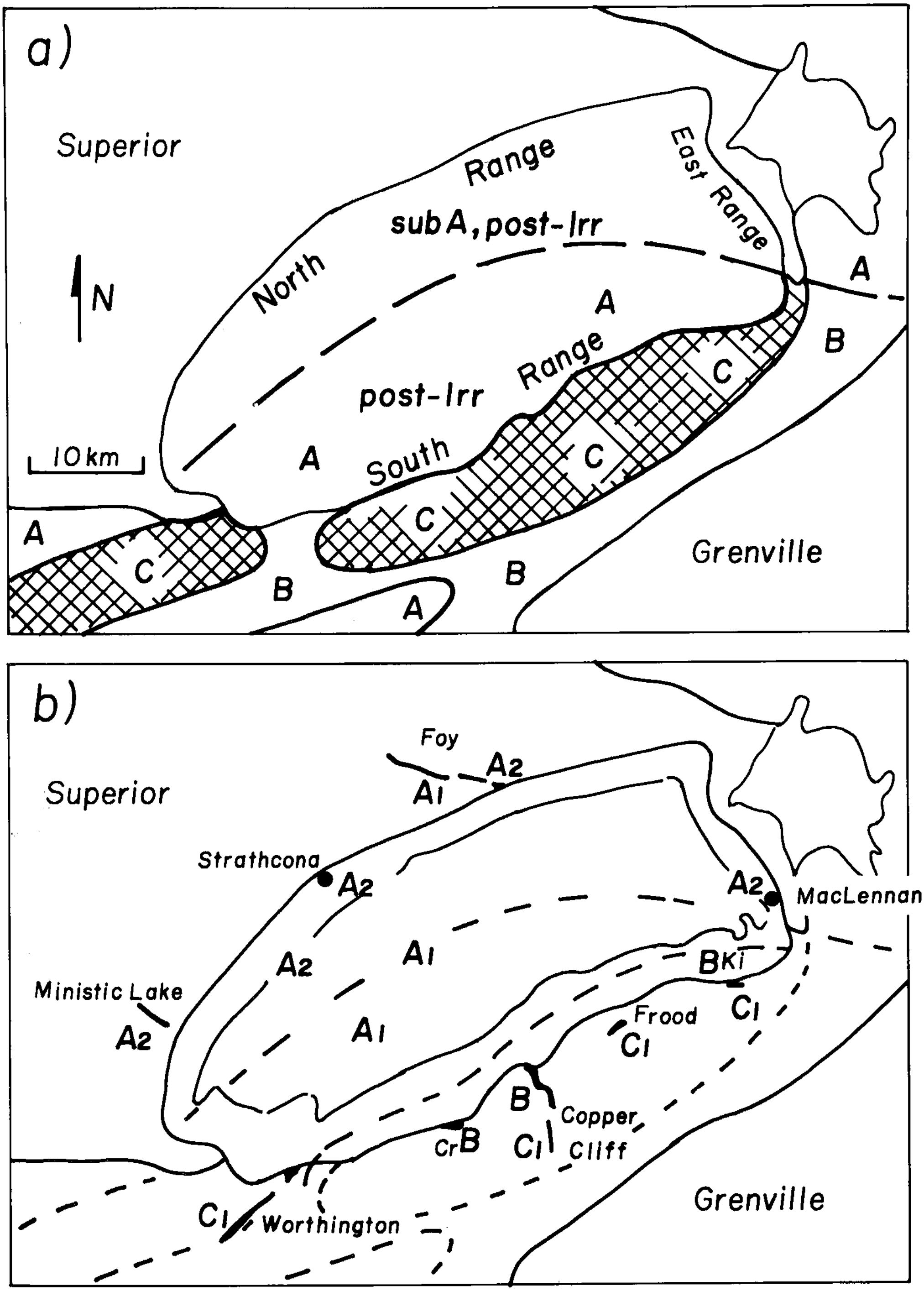

FIG. 1. Metamorphic geology of the Sudbury area. a) Metamorphic zones of Card (1978a, Fig. 3), which include pre-Irruptive metamorphic zones in Southern Province footwall (A, low- to middle-greenschist facies; B, middle- to upper-greenschist facies; C, almandine-amphibolite facies) and post-Irruptive (post-Irr) zones in Sudbury Basin (sub A, subgreenschist facies; A, low- to middle-greenschist facies). b) Metamorphic zones from present study of the Sudbury Igneous Complex, associated footwall, and Whitewater Group: A_1, low-greenschist facies; A_2, middle- and upper-greenschist facies; B, epidote-amphibolite facies; C_1, low-amphibolite facies; Ki, Kirkwood; Cr, Creighton.

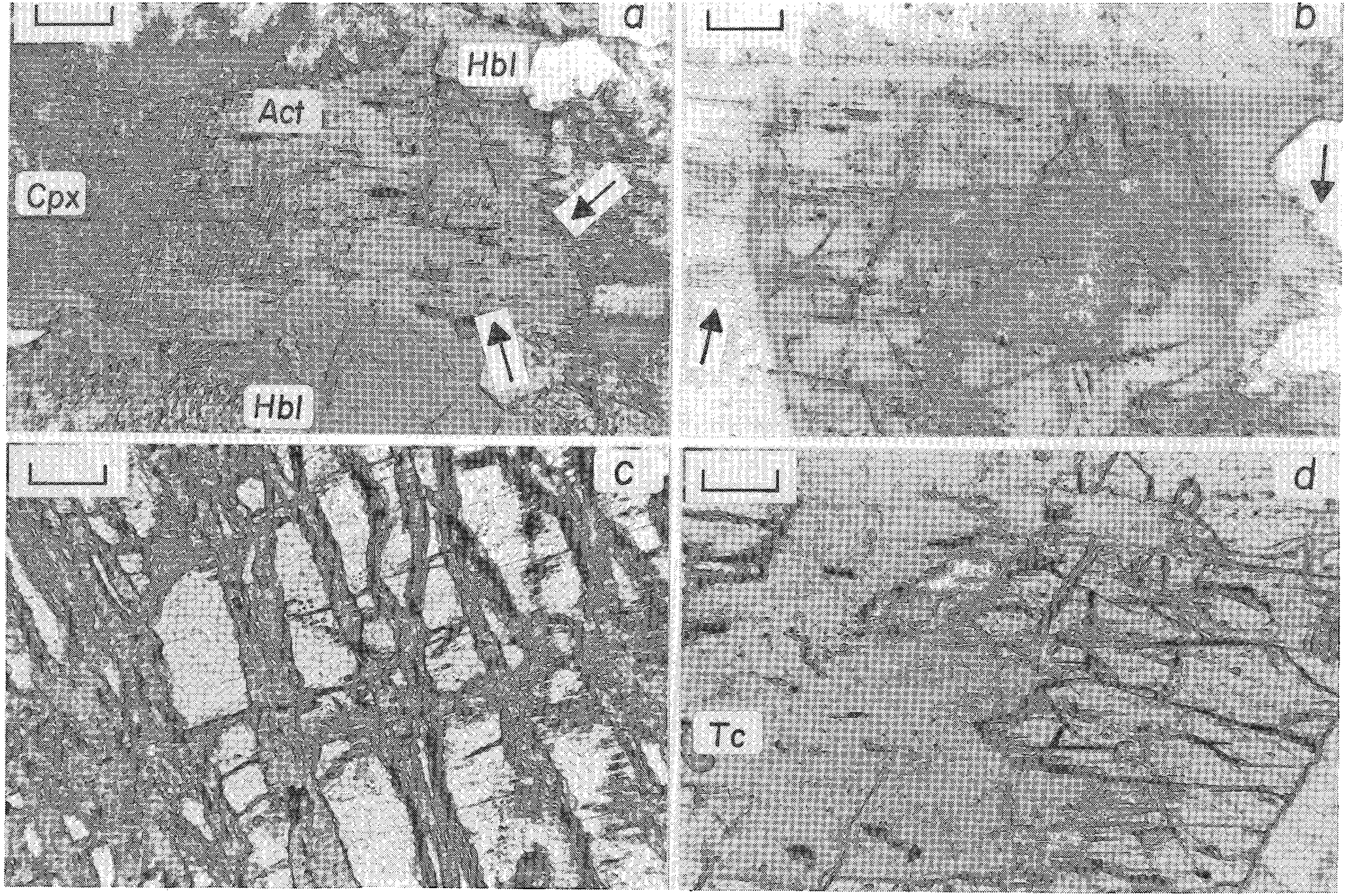

FIG. 2. Textural details in altered rocks of the Sudbury Igneous Complex. a) Complex clinopyroxene (Cpx) – amphibole intergrowth; Hbl, hornblende; arrows, actinolitic hornblende; Act, actinolite; MacLennan oxide-rich gabbro, GT–24. b) Primary ferro-edenite with overgrowth of actinolitic hornblende (arrows); MacLennan transition zone, GT–17. c) Bronzite veined with talc; Strathcona pyroxenite, FF207A. d) Hypersthene grain with core of talc (Tc); Strathcona felsic norite, FF25C.

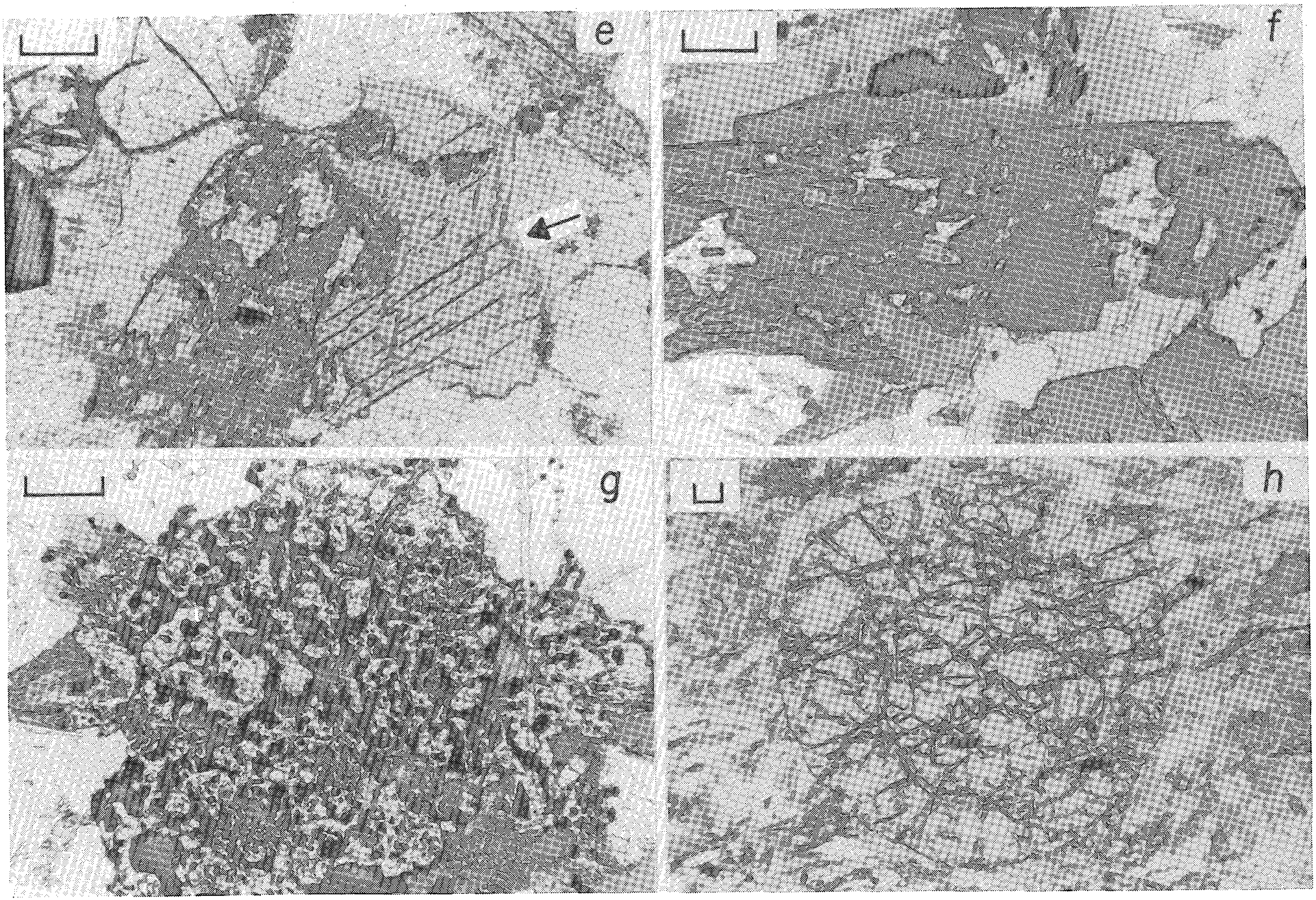

FIG. 2. (continued): Textural details in altered rocks of the Sudbury Igneous Complex. e) Rim of actinolitic hornblende (arrow) on altered hypersthene; Strathcona felsic norite, FF25C. f) Ferroan pargasite; Frood mine quartz diorite, 424. g) Almandine garnet intergrown with Ni–Cu sulfides; Frood mine, exotic fragment of fractionated quartz diorite, FD2. h) Almandine garnet, fractionated quartz diorite, Kirkwood area, C840113.

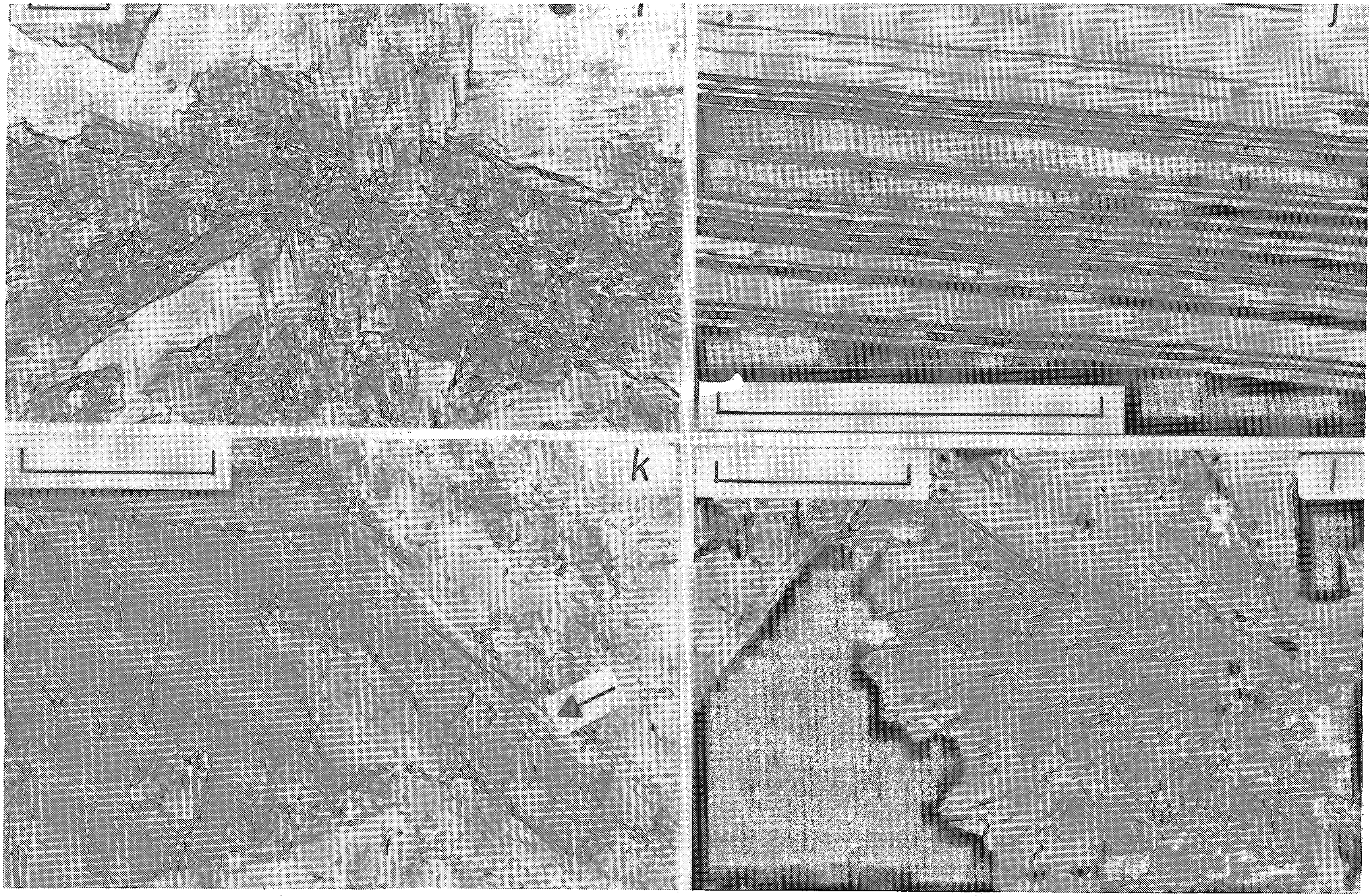

FIG. 2. (continued): Textural details in altered rocks of the Sudbury Igneous Complex. i) Blue-green hornblende grains with dark blue-green tschermakitic hornblende rim; Copper Cliff quartz diorite, CSX113A, site 16. j) Lamellar intergrowth of biotite (light) and chlorite (dark); Worthington fractionated quartz diorite, BSW40–B, site 6. k) Primary brown edenite selectively replaced by blue-green actinolitic hornblende (arrow) at tip; Foy quartz diorite, BSZ199A. l) Fan-shaped aggregates of actinolite and actinolitic-hornblende with (later) Ni–Cu sulfides (dark); Foy quartz diorite, BSZ199A. Transmitted light; scale bar is 0.1 mm.

Card (1978a) and Brocoum & Dalziel (1974) recognized that sedimentary and volcanic rocks of the Whitewater Group in the Sudbury basin have been metamorphosed to the greenschist facies, the grade decreasing progressively northward from the upper-greenschist facies in South Range hanging-wall rocks to lower-greenschist or subgreenschist facies along the northern rim of the basin. However, Card (1978a) and Brocoum & Dalziel (1974) disagreed on the timing of the post-Nipissing diabase metamorphism and deformation events in the Sudbury area. Card (1978a) 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 assemblages of metamorphic minerals in 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) and are associated with a proposed separate (Hudsonian) orogeny. Card's Penokean and Hudsonian metamorphic zones in the Sudbury area are summarized in Figure 1a. 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. No attempt has been made to distinguish between a Penokean orogeny and a Hudsonian orogeny in Michigan, but rather "Penokean" is used to refer to all Pre-Keweenawan diastrophism affecting Late and Middle Proterozoic rocks (Cannon 1973).

The metabasite assemblages at the Frood mine (Fleet & Barnett 1978) and at Kirkwood (Thomson *et al.* 1985) are consistent with a post-Irruptive, prograde metamorphic overprint in the Sudbury area, which appears to have climaxed at medium-grade conditions to the south of the Irruptive and faded northward. The present study on both Irruptive and offset rocks of the SIC shows that the zonal nature of this overprint is consistent with the zonal pattern of the metamorphism of the Southern Province footwall rocks (Fig. 1), and thereby establishes that the Penokean orogeny is post-Irruptive in age in the Sudbury area.

Petrography and Mineral Chemistry

Rock samples of the Sudbury Igneous Complex (SIC) were obtained from a variety of sources, but principally from the study of Morris (1982). They were investigated by transmitted- and reflected-light microscopy (Fig. 2) and electron-microprobe analysis of selected mineral grains. 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).

An abridged description of the metabasite assem-

TABLE 1. REPRESENTATIVE COMPOSITIONS OF CALCIC AMPHIBOLE FROM THE SUDBURY IGNEOUS COMPLEX

Analysis Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Locality	MacLennan					Strathcona			Frood	Kirkwood area		Copper Cliff			Worthington		Creighton	Foy	
SiO_2	55.11	53.72	50.44	48.64	49.70	54.44	52.87	48.77	39.32	41.13	41.01	47.59	43.21	41.32	42.71	42.67	38.21	47.91	51.36
TiO_2	0.09	0.15	0.54	0.32	0.04	0.03	0.53	0.73	0.13	0.27	1.86	0.48	0.63	0.30	0.38	0.40	0.77	1.54	0.76
Al_2O_3	1.36	0.89	3.77	3.30	4.30	1.51	3.40	5.44	17.58	16.66	13.67	5.83	11.94	15.21	14.23	14.01	12.46	6.41	4.96
Fe_2O_3*	0.21	1.01	2.65	2.81	1.04	0.37	1.78	2.45	3.38	2.97	3.82	3.08	4.09	1.87	0.91	1.48	4.42	2.80	2.91
FeO	17.64	19.54	14.39	23.50	24.33	18.71	8.28	10.98	21.87	20.71	20.48	14.83	17.64	19.63	16.76	17.94	22.84	12.00	11.36
MnO	0.63	0.42	0.32	0.34	0.47	0.73	0.06	0.16	0.20	0.35	0.43	0.43	0.26	0.18	0.27	0.25	0.09	0.17	0.20
MgO	16.91	12.86	13.75	8.26	6.69	18.25	18.46	14.70	2.88	4.22	5.05	11.45	7.38	5.56	7.76	7.32	4.01	14.20	14.70
CaO	6.68	9.66	10.68	9.20	11.68	3.20	11.62	11.27	10.99	11.11	10.43	12.49	11.50	11.71	11.84	12.05	11.49	11.13	11.13
Na_2O	0.19	0.47	1.08	0.95	0.29	0.25	1.19	1.45	1.59	1.40	1.71	0.66	0.83	1.28	1.32	1.51	1.51	1.84	1.18
K_2O	0.03	0.06	0.26	0.27	0.36	0.03	0.33	0.71	0.47	0.56	0.46	0.53	0.93	0.71	0.50	0.34	1.95	0.98	0.48
Total	98.85	98.78	97.88	97.59	98.90	97.52	98.52	96.66	98.41	99.38	98.92	97.37	98.41	97.77	96.68	97.97	97.75	98.98	99.04
Structural Formulae On The Basis of 23 Oxygens																			
Si	7.88	7.87	7.40	7.46	7.52	7.87	7.47	7.18	6.02	6.18	6.23	7.11	6.50	6.29	6.45	6.41	6.07	6.96	7.34
IVAl	0.12	0.13	0.60	0.54	0.48	0.13	0.53	0.82	1.98	1.82	1.77	0.89	1.50	1.71	1.55	1.59	1.93	1.04	0.66
VIAl	0.11	0.02	0.05	0.06	0.29	0.12	0.03	0.13	1.20	1.14	0.68	0.14	0.62	1.01	0.98	0.89	0.40	0.06	0.18
Ti	0.01	0.02	0.06	0.04	0.01	0.00	0.06	0.08	0.02	0.03	0.21	0.05	0.07	0.03	0.04	0.05	0.09	0.17	0.08
Fe^{3+}*	0.02	0.11	0.29	0.32	0.12	0.04	0.19	0.27	0.39	0.34	0.44	0.35	0.46	0.21	0.10	0.17	0.53	0.31	0.31
Fe^{2+}	2.11	2.39	1.76	3.01	3.08	2.26	0.98	1.35	2.80	2.60	2.60	1.85	2.22	2.50	2.12	2.25	3.04	1.46	1.36
Mg	3.60	2.81	3.01	1.89	1.51	3.93	3.89	3.23	0.66	0.95	1.14	2.55	1.66	1.26	1.75	1.64	0.95	3.07	3.13
Mn	0.08	0.05	0.04	0.04	0.06	0.09	0.01	0.02	0.03	0.04	0.06	0.05	0.03	0.02	0.03	0.03	0.01	0.02	0.02
Ca	1.02	1.52	1.68	1.51	1.89	0.50	1.76	1.78	1.80	1.79	1.70	2.00	1.85	1.91	1.92	1.94	1.96	1.73	1.71
Na	0.05	0.13	0.31	0.28	0.09	0.07	0.33	0.41	0.47	0.41	0.50	0.19	0.24	0.38	0.38	0.44	0.46	0.52	0.33
K	0.01	0.01	0.05	0.05	0.07	0.01	0.06	0.13	0.09	0.11	0.09	0.10	0.18	0.14	0.10	0.07	0.40	0.18	0.09

* Ferric iron estimated using "midpoint" by method of Papike et al. (1974)
Sample numbers: 1, GT-50; 2, GT-35; 3, GT-38; 4, GT-19; 5, GT-3; 6, FF121B; 7, FF25C; 8, FF121B; 9, FD2; 10, C840113; 11, C840113; 12, SX1-51; 13, CSX115A; 14, CSX115A; 15, BSW71-A; 16, BSW36-B; 17, NB1-2; 18, BSZ199A; 19, BSZ199A

blages is included in this section; more complete descriptions are given with sample numbers and locations in the Appendix, which is available at nominal charge from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ontario K1A 0S2. Sample localities (Fig. 1b) are organized on the basis of the two lithologically distinct units: the Irruptive, and the offset dykes and sublayer (with associated Southern Province footwall rocks). Alteration assemblages of the Whitewater Group are included to permit extrapolation of isograds of the SIC to the Sudbury basin. The primary petrographic features of the Irruptive, sublayer, and offset dykes have been described by, respectively, Naldrett *et al.* (1970), Pattison (1979) and Souch *et al.* (1969). Other aspects of Sudbury area geology are discussed in Guy-Bray (1972) and Pye *et al.* (1984).

The composition of plagioclase in altered rocks of the SIC is not particularly useful as an independent estimate of metamorphic grade and, therefore, little emphasis is placed on documenting it. Thomson *et al.* (1985) reported that primary plagioclase only participates in limited reaction in the alteration of norite at Kirkwood except in sheared and foliated rocks. Even in largely recrystallized medium-grade offset rocks in the South Range footwall, a vestige of diffusion-related compositional zoning is retained in plagioclase laths. The composition of plagioclase in these rocks is andesine, and is essentially unchanged from that of the primary quartz diorite and fractionated quartz diorite. Under low-grade conditions, primary plagioclase tends to react out with excess fluid to yield an alteration assemblage in which the sodic plagioclase component is too fine grained and intimately related with the other reaction products for analysis by the electron-microprobe technique.

SIC rocks are complicated, and interpretation of the postmagmatic alteration, with recognition of minerals and mineral assemblages sensitive to metamorphic grade, is made more difficult by the broad variation in the pervasiveness of the metamorphic alteration, with frequent retention of primary characteristics. Careful documentation of petrographic features, as presented in the Appendix, is essential for meaningful correlation from one locality to another. Most Irruptive rocks and some of the North Range offset rocks appear on superficial examination to be unmetamorphosed. However, South Range offset rocks that are unquestionably SIC in origin are also unquestionably now metamorphic amphibolites and epidote amphibolites.

IRRUPTIVE ROCKS

South Range: Kirkwood mine

Metamorphic minerals in green norite include amphibole, epidote, scapolite, biotite, chlorite, titanite, sodic plagioclase and recrystallized quartz. The amphibole assemblage consists of aggregates of colorless actinolite or pale blue-green actinolitic hornblende, after hypersthene and augite, with a rim of dark blue-green magnesio-hornblende (Fig. 3c; Thomson *et al.* 1985, Table 1). Plagioclase is incompletely reacted, except within local shear-zones. Analogous mineral assemblages (blue-green tschermakitic hornblende with a minor green-brown hornblende core + epidote + quartz + titanite + plagioclase) characterize the Elsie Mountain greenstone footwall rocks.

East Range: MacLennan

Although primary textures are generally preserved, the mineral grains themselves are extensively altered. Only quartz and apatite have a fresh appearance. Plagioclase is very largely altered to a mixture of sericite, fine-grained epidote and a fine-grained green amphibole (which appears to be actinolitic hornblende). Relict unreplaced areas have a patchy inhomogeneity that may reflect incomplete recrystallization during metamorphism. Hypersthene commonly is entirely replaced by a low-Al amphibole (Fig. 3b) and talc, analogous to the alteration of hypersthene in black norite at Kirkwood (Thomson *et al.* 1985) and in norite from the Strathcona section. Much of the low-Al amphibole in hypersthene pseudomorphs at MacLennan has a fibrous or feathery habit and appears to be a two-phase intergrowth of cummingtonite and actinolite (column 1, Table 1). Clinopyroxene is replaced by colorless to pale green actinolite and darker blue-green actinolitic hornblende in gabbroic rocks and by the corresponding varieties in overlying rocks (columns 2 to 4, Table 1).

Primary hornblende–edenite has a slightly bleached (incipiently reacted) appearance and is partly replaced or overgrown by actinolitic amphibole (actinolite – actinolitic hornblende – ferro-actinolite – ferro-actinolitic hornblende; Fig. 2a, b; column 5, Table 1; Fig. 3b). Actinolitic amphibole has a complex textural relationship with hornblende in MacLennan Irruptive rocks. Where actinolitic amphibole is associated with clinopyroxene, green-brown primary hornblende forms a patchy, discontinuous rim to pale blue-green actinolitic amphibole (Fig. 2a). The textural relationship of Figure 2a is fairly typical of complex clinopyroxene–amphibole intergrowths: actinolitic amphibole appears to have replaced both clinopyroxene and primary hornblende.

Detailed electron-microprobe analysis of the amphiboles in the MacLennan Irruptive rocks, especially of the dark blue-green grains, reveals a complete absence of an aluminous phase (Table 1, Fig.

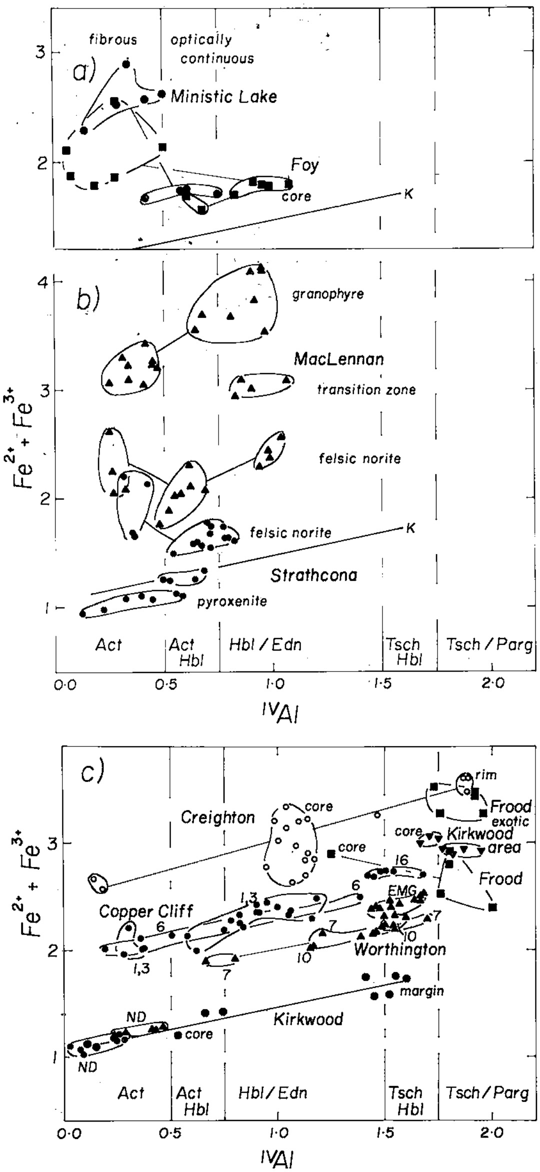

FIG. 3. Variation of total Fe cations (Fe^{2+} + Fe^{3+}) with ^{IV}Al in amphiboles from altered rocks of the Sudbury Igneous Complex. Data for Kirkwood and Frood are selected compositions for individual rocks; other data-points grouped together are individual compositions from microprobe spot-analyses for one or more rocks from selected sample locations and rock types: 1, 3, 6, *etc.*, sample sites of Morris (1982); EMG, Elsie Mountain greenstone, Worthington offset; ND, Nipissing diabase, Copper Cliff and Worthington offsets; Act, actinolite; Act Hbl, actinolitic hornblende; Hbl, hornblende; Edn, edenite; Tsch Hbl, tschermakitic hornblende; Tsch, tschermakite; Parg, pargasite. In 2a) and 2b), actinolite (or actinolite–cummingtonite intergrowth) replacing hypersthene commonly has a fibrous habit, whereas actinolite and actinolitic hornblende associated with clinopyroxene and hornblende–edenite is optically continuous.

3b). Intensity of the blue-green color is associated with Fe-enrichment as well as Al-enrichment. All grains of fine-grained dark blue-green amphibole analyzed are ferro-actinolitic hornblende. Thus, the aluminous blue-green hornblende of the offset rocks to the south of the SIC and of the South Range is not present at MacLennan. Whereas a low-Al calcic amphibole + hornblende assemblage is present, we feel that the textural evidence favors a primary (late magmatic) origin for the latter phase, perhaps with some compositional readjustment during metamorphism.

Chlorite and secondary biotite are present only in minor amounts in felsic norite and oxide-rich gabbro, but chlorite with epidote grains are dominant over amphibole and clinopyroxene in the granophyre.

North Range: Strathcona

In a pyroxenite exotic inclusion, clinopyroxene and plagioclase are relatively fresh, but bronzite is veined with talc (Fig. 2c). Minor interstitial pale blue-green amphibole, which is present as both optically continuous and fibrous, matted grains, is actinolite and actinolitic hornblende (Fig. 3b).

Plagioclase is relatively fresh in the felsic norite at Strathcona, but Naldrett *et al.* (1970) noted that sericite alteration is pervasive in the oxide-rich gabbro and alteration to epidote is fairly extensive in the upper part of the oxide-rich gabbro and extreme lower part of the granophyre. Hypersthene grains are largely altered to talc (Fig. 2d) or, less commonly, to a mixture of talc and fibrous amphibole, which appears to be a two-phase mixture of cummingtonite and actinolite (column 6, Table 1). Ophitic augite appears fresh and unaltered. However, it does have a discontinuous rim of pale blue-green amphibole that is optically continuous at grain margins and forms a blotchy intergrowth with the augite toward the grain interiors. The optically continuous pale blue-green amphibole associated with augite and hypersthene grains and interstitial to pyroxene and plagioclase in the Strathcona norite appears to be a late magmatic product based on textural observations. However, its composition varies from actinolite, to actinolitic hornblende, to hornblende (columns 7 and 8, Table 1; Fig. 3b); the broad rim on hypersthene of Figure 2e, for example, is actinolitic hornblende. Thus most of the optically continuous pale blue-green amphibole grains in the Strathcona felsic norite have compositions consistent with low-grade metamorphism and appear to have developed by replacement of pre-existing brown hornblende and edenite. This conclusion is consistent with the presence of apparent late-magmatic brown amphibole at MacLennan, Ministic Lake and Foy. Occasional twinned or fibrous blue-green actinolite and actinolitic hornblende probably developed by progressive alteration of hypersthene. Interstitial brown biotite, with 3.5–4.0 wt.% TiO_2 and interpreted as being late magmatic in origin, is partly replaced by a green biotite (0.5–1.0 wt.% TiO_2) in optical continuity with it. Minor amounts of chlorite are present in all samples.

Offset Dykes and Sublayer

Frood–Stobie offset

Frood mine rocks are amphibole–biotite–plagioclase–quartz rocks with minor (retrograde) chlorite; actinolite and epidote are absent. Blue-green ferroan pargasite (Fleet & Barnett 1978, Table 1; Fig. 3c) is present as a broad continuous rim on green hornblende and on aggregates of medium-scale ragged cummingtonite, and as ragged poikiloblastic grains (Fig. 2f). Amphibole compositions are summarized in Figure 3c.

The felsic (quartz–feldspar) component of the original quartz diorite is largely recrystallized. An interstitial micrographic intergrowth, which characterizes quartz diorite at a lower grade as a relict primary texture, is absent. Plagioclase laths are commonly overgrown by large grains of quartz and have a diffuse zonation to a more calcic core. The composition of plagioclase is An_{30-35}.

An exotic inclusion of quartz diorite (FD2) from the vicinity of the 12 stope is significant because it contains almandine garnet. FD2 is a fractionated quartz diorite rock in which plagioclase and amphibole are, respectively, subordinate to quartz and biotite. The amphibole assemblage is now dark blue-green ferro-pargasite (column 9, Table 1; Fig. 3c) with minor cummingtonite. Almandine garnet accounts for 2–5% of the rock. It occurs as scattered porphyroblasts that are idioblastic against biotite and have ragged outlines against quartz, and are commonly in the form of a complex replacement-like intergrowth with later Ni–Cu sulfides (Fig. 2g). In the Frood mine, almandine garnet is pale pink in plane-polarized light, and its composition (almandine$_{74}$grossular$_{12}$pyrope$_{4}$spessartine$_{10}$) is consistent with almandine-zone garnet.

Dyke rock in the Kirkwood area

In the Kirkwood area there is a small late-stage SIC dyke complex, which is generally concordant to the strike of the Irruptive but appears in outcrop to cross-cut both Irruptive and adjacent offset rocks.

The dyke rock has a fractionated quartz diorite composition and has been extensively recrystallized and deformed. The present assemblage of minerals is amphibole + biotite + garnet + plagioclase + quartz with minor chlorite, epidote and muscovite. The amphibole has a pronounced preferred orientation and consists of prismatic and acicular grains of dark blue-green ferro-pargasite (column 10, Table 1) with an apparently relict light brown ferro-pargasite core (column 11, Table 1; Fig. 3c). The garnet has the approximate composition (almandine$_{70}$grossular$_{8}$pyrope$_{13}$spessartine$_{9}$) and occurs as rounded and commonly ragged porphyroblasts in augen-type structures (Fig. 2h). It is more inhomogeneous and slightly less almandine-rich than the almandine in the Frood mine. The recrystallized groundmass plagioclase has a composition of about An_{30}.

Thus the small dyke-like feature in the Kirkwood area is a strongly foliated, almost schistose, almandine garnet amphibolite. Like the exotic inclusion of fractionated quartz diorite from the Frood mine, it is Fe-rich, and the important grade-indication assemblage is ferro-pargasite + almandine garnet.

Copper Cliff offset

All of the offset rocks at Copper Cliff are recrystallized quartz diorite. They exhibit a marked variation in grain size from coarse to fine, which correlates with increasing proximity to the footwall contact (Morris 1982). Interestingly, they exhibit a progressive increase in the grade of metamorphism with increasing distance from the Irruptive. Many of these rocks are completely recrystallized, and the remainder are largely recrystallized to the extent that primary relict textural features are limited to plagioclase laths, micrographic intergrowth and organization of amphibole grains into millimetre-sized patchy and elongated zones (which presumably represent pre-existing ferromagnesian phases). Relict plagioclase laths are irregularly zoned in the manner of South Range green norite (Thomson *et al.* 1985) and have sutured grain-boundaries. The micrographic intergrowth is largely altered to a sieve-textured intergrowth.

Samples closest to the Irruptive are biotite – amphibole – epidote – plagioclase – quartz – titanite rocks with minor chlorite. The proportion of brown biotite to amphibole varies markedly: in general, biotite is more abundant than (and even locally dominant over) amphibole closest to the Irruptive and becomes subordinate with increasing distance away from it. Epidote is present in abundance as scattered idioblastic grains, making up more than 25% of many rocks. The amphibole assemblage is blue-green low-Al hornblende and colorless to pale blue-green actinolite or actinolitic hornblende (Fig. 3c). Blue-green hornblende (column 12, Table 1) is present as medium-sized irregular and prismatic grains and as irregular aggregates of these grains. In coarser-grained rocks it is also poikiloblastic. All textural varieties may have a narrow selvage of dark blue-green aluminous hornblende.

Copper Cliff samples farthest away from the Irruptive are amphibole – biotite – plagioclase – quartz – titanite rocks, with occasional chlorite. Epidote is essentially absent, and their overall appearance is similar to some of the Frood–Stobie offset rocks. The amphibole assemblage is now blue-green hornblende with a broad dark blue-green tschermakitic hornblende rim (columns 13 and 14, Table 1; Figs. 2i, 3c).

Nipissing diabase footwall rocks from location CX15 (Morris 1982, Fig. 5), which is remote from the Irruptive, are coarse-grained actinolite-plagioclase rocks, with minor clinozoisite along plagioclase grain-boundaries, and muscovite. Actinolite compositions are summarized in Figure 3c. Many actinolite grains are complexly twinned in the manner of altered hypersthene in South Range green norite (Thomson *et al.* 1985), and others are optically continuous, with a single {100} twin in the manner of altered clinopyroxene. Thus the pre-existing rocks appear to have been gabbro–pyroxenite. The Sudbury dyke rocks at Copper Cliff are fresh olivine gabbros and olivine diabases (*e.g.*, Palmer *et al.* 1977). Postmagmatic alteration is restricted to narrow veins of green saponite and sporadic replacement of olivine grains by a smectite–illite intergrowth.

Worthington offset

Rocks of the Worthington offset emphasize the local nature of the metamorphic alteration of SIC rocks to the south of the Irruptive. A sample from site 6 of Morris (1982, Fig. 6) is a muscovite – epidote – chlorite – biotite – quartz rock (*e.g.*, Fig. 2j). In marked contrast, offset rocks from sites 7 and 10 of Morris (1982, Fig. 6) are very similar to the highest-grade rocks from the Copper Cliff offset, having the assemblage amphibole + biotite + plagioclase + quartz with minor titanite; epidote and actinolite are absent. The amphibole is blue-green tschermakitic hornblende (column 15, Table 1; Fig. 3c); low-Al hornblende and actinolitic hornblende are present only in very minor amounts. Recrystallized plagioclase is An_{25-30}.

A sample of Nipissing diabase footwall contact rock is virtually identical to equivalent rocks from the Copper Cliff offset. Two other samples of the footwall-contact rocks from site 5 (Morris 1982, Fig. 6) are Elsie Mountain greenstone. These amphibolites are very similar to the footwall Elsie Mountain greenstone at the Kirkwood mine (Thomson *et al.* 1985), except that they are more uniformly and extensively metamorphosed. The amphibole assemblage is now single-phase blue-green ferro-tschermakitic hornblende (column 16, Table 1; Fig. 3c); low-Al calcic amphibole and ordinary hornblende are absent.

Creighton mine sublayer

Dark blue-green ferro-pargasite (column 17, Table 1) forms a continuous narrow rim on small rounded grains of augite and a discontinuous patchy marginal replacement on green hornblende. It is also present as small prismatic inclusions throughout the felsic (quartz–feldspar) component. A few grains of augite are altered to actinolite. The amphibole chemistry is summarized in Figure 3c. Epidote is generally absent, although a few scattered grains are present in some of the rocks, and almandine garnet has not been observed. Smaller plagioclase grains are about An_{30}.

Ministic Lake offset

The postmagmatic alteration is superficially similar to that of Foy offset rocks. Plagioclase laths are replaced by a very fine-grained mixture of epidote and sericite. Presumed primary hypersthene grains have been replaced by fibrous actinolite and fibrous, matted two-phase cummingtonite + actinolite, and, occasionally, by patches of talc. Subhedral primary-textured amphibole grains now consist of a core of brown edenite that grades through green hornblende to a discontinuous blue-green actinolitic hornblende rim. This textural association clearly indicates that the two-phase actinolitic hornblende + hornblende–edenite intergrowth in SIC rocks is not an equilibrium assemblage. Green-brown and green low-Al hornblende and blue-green actinolitic hornblende form by the progressive incomplete replacement of pre-existing primary brown edenite. Pale green chlorite is present interstitial to the replaced plagioclase laths. In an annealed exotic inclusion, the original low-Al pale hornblende is partly replaced by optically continuous, fibrous and matted actinolite and actinolitic hornblende (Fig. 3a).

Foy offset

Quartz diorite is extensively or completely recrystallized to epidote – biotite – chlorite – amphibole – albite – quartz – calcite rocks. Hypersthene may be entirely replaced by fibrous pale green actinolite (Fig. 3a). Subhedral and partly skeletal brown edenite (column 18, Table 1) is partly replaced by optically continuous blue-green actinolite (Figs. 2k, l; column 19, Table 1).

WHITEWATER GROUP

In the Onaping tuff from the type locality in Dowling Township, the alteration assemblage is actinolite + chlorite + quartz + feldspar with minor titanite and sericite after plagioclase. Actinolite occurs in radiating acicular masses. Onwatin slate from a locality south of Larchwood consists of muscovite, chlorite and quartz, with minor clinozoisite.

The sheet silicate minerals are very fine grained, and the rock has recrystallized without losing its slaty characteristic. Chelmsford grit from east of Larchwood and east-central Dowling Township is an incipiently to moderately deformed gritstone, with the characteristic alteration-assemblage muscovite + chlorite + calcite. Chlorite commonly forms a complex lamellar intergrowth with muscovite and with a second mica phase, which appears to be biotite.

Discussion

Amphibole chemistry

The variation in the composition of calcic amphibole in altered rocks of the Sudbury Igneous Complex (SIC) is reported with a plot of total Fe cations *versus* ^{IV}Al for greenschist-facies assemblages in Figures 3a, b and for epidote-amphibolite and low-amphibolite-facies assemblages in Figure 3c. This plotting procedure is analogous (but not identical) to the $[(R^{3+}+R^{2+}) \rightleftharpoons Mg]$ *versus* ^{IV}Al plot of Grapes & Graham (1978, Fig. 3A) and, along with the (^{VI}Al + Fe^{3+} + Ti) *versus* ^{IV}Al plot of Figure 4, permits comparison of octahedral (*M*) site (*M* = Mg,Fe^{2+}, Al, Fe^{3+},Ti) and tetrahedral (*T*) site (*T* = Si,Al) substitutions; the small amount of Fe^{2+} in the *M*(4) site is ignored. Figure 3c reveals a characteristic trend of increasing total Fe cations (decreasing Mg) with increasing ^{IV}Al. This is consistent with the reported increase in Fe^{2+}/Mg and ^{VI}Al with metamorphic grade (Wiseman 1934, Robinson *et al.* 1982). In the Sudbury Igneous Complex, this trend is less well defined if either Fe^{2+} or Mg alone is used, which suggests either a hastingsite or a ferri-tschermakite *component* in the calcic amphibole substitution.

The variation in total Fe cations among calcic amphiboles from different localities and rock types largely reflects the variation in whole-rock Fe/(Fe + Mg) value: Figure 4 shows that the effect of variation in (^{VI}Al + Fe^{3+} + Ti) with locality and rock type is minor. Since the metabasites of the SIC exhibit an unusually wide range in primary composition (ultrabasic, basic, intermediate, acidic), the variation due to whole rock Fe/(Fe + Mg) ratio would naturally tend to obscure the systematic increase in total Fe cations with ^{IV}Al if data for individual epidote amphibolites had not been identified in Figure 3c.

Within individual greenschist-facies rocks, there is a tendency for fibrous actinolite, which has replaced pre-existing hypersthene, to have a higher total Fe content than coexisting actinolite and actinolitic hornblende, which has replaced pre-existing clinopyroxene and hornblende – edenite (Figs. 3a, b). This behavior seems to reflect differences in the compositions of the primary minerals: hypersthene is systematically more Fe-rich than coexisting augite in the Sudbury Igneous Complex (*e.g.*, Naldrett *et al.* 1970).

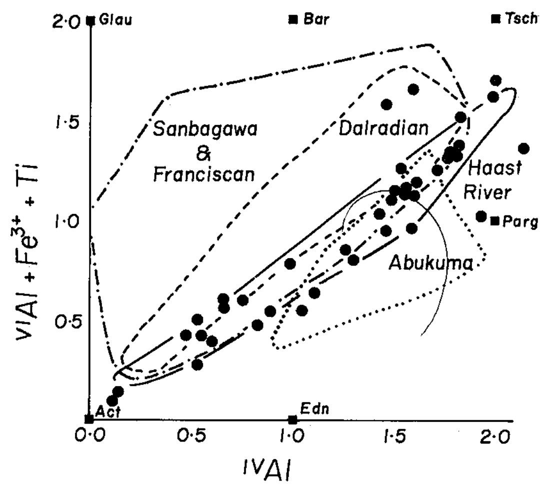

FIG. 4. Comparison of (^{VI}Al + Fe^{3+} + Ti) *versus* ^{IV}Al in amphiboles of the Sudbury Igneous Complex, with data for reference metamorphic terranes of Laird & Albee (1981, Fig. 8): SIC data are from Table 1, Fleet & Barnett (1978, Table 1) and Thomson *et al.* (1985, Table 1): Glau, glaucophane: Bar, barroisite; other abbreviations as in Figure 3.

Magnesio-hornblende – ferro-edenite in these greenschist-facies rocks is interpreted as an incompletely reacted relict primary phase. The composition of hornblende – edenite changes progressively with pervasiveness of alteration toward actinolitic hornblende in low-grade rocks and toward tschermakite – pargasite in medium-grade rocks. Commonly, a "relict" core is present, even in the essentially completely recrystallized low-amphibolite-facies rocks of the Frood mine and the dyke in the Kirkwood area.

In the Strathcona norite, the pale blue-green optically continuous calcic amphibole appears to have the appropriate color and composition for low-grade alteration, yet its textural relations could be interpreted as magmatic or late magmatic. Our observations suggest that the pale blue-green amphibole is a pseudomorph of pre-existing magmatic brown amphibole. The amphibole textures and compositions of Foy and Ministic Lake rocks are particularly significant in this regard, because they show incomplete replacement of magmatic brown edenite by optically continuous blue-green actinolite (Fig. 2k). With a slightly higher grade and more pervasive metamorphism, this replacement would have gone to completion.

In greenschist-facies rocks of the Sudbury Igneous Complex, the color of optically continuous calcic amphibole changes progressively with replacement: from brown to green-brown to green to pale blue-green. Ti and Fe contents appear to be important factors in color development, which suggests that $Fe^{2+} \rightarrow Ti^{4+}$ charge transfer might be more important than $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer (*cf.* Hawthorne 1981), at least in brown calcic amphibole. In the Kirkwood area dyke-rock, the core and margin of calcic amphibole grains have similar overall compositions (*e.g.*, Fig. 3c), but the relict brown core has about 2.0% TiO_2 and the broad dark blue-green margin has only about 0.2% TiO_2. There seems to be a threshold of Ti content below which the color of calcic amphibole is green-brown or green.

The data for individual rocks in the epidote-amphibolite facies exhibit an almost complete variation in ^{IV}Al content across the proposed calcic amphibole miscibility-gap (*e.g.*, Grapes & Graham 1978, Robinson *et al.* 1982, Maruyama *et al.* 1983). The data for Copper Cliff, in particular, relate to the same bulk composition and P–T conditions. The more Mg-rich calcic amphiboles from Kirkwood do tend to have a bimodal composition, but even here many individual spots analyzed by microprobe have intermediate compositions [Thomson *et al.* 1985, Fig. 4; note that the caption to this figure incorrectly refers to the reference line as the edenite substitution. It is, in fact, the pargasite substitution: $\square(Mg)Si_2 = Na(^{VI}Al)^{IV}Al_2)$]. However, we recognize that the presence and compositional range of the calcic amphibole solvus (or transition loop) are expected to be dependent on variation in bulk composition and P–T conditions among samples (*e.g.*, Maruyama *et al.* 1983).

Metabasite assemblages

The overall purpose of the present paper is to compare the postmagmatic alteration of the Sudbury Igneous Complex with the Penokean metamorphism of the Southern Province footwall, and thus establish the Sudbury area as a prograde metamorphic terrane. This requires identification of assemblages of metamorphic minerals and qualitative comparison with metabasites from established metamorphic terranes. A quantitative analysis of the metamorphic processes in terms of mineral reactions, P–T conditions and paths, fluid/rock ratios, *etc.* (*e.g.*, Laird & Albee 1981, Robinson *et al.* 1982, Ferry 1985) will be attempted in a subsequent study. We recognize that rock composition affects the stability of amphibolites, and note that the present qualitative estimates of P–T conditions refer to the "common assemblage" (cf. Robinson *et al.* 1982).

The metabasite assemblages in altered rocks of the Sudbury Igneous Complex are summarized in Figure 5. The lower-greenschist-facies (A_1 zone) assemblage is characterized by epidote + chlorite + biotite (green/brown) + calcite + (albite) + quartz; actinolite is absent. This assemblage is restricted in the present investigation to the Foy offset and to the Worthington offset, site 6.

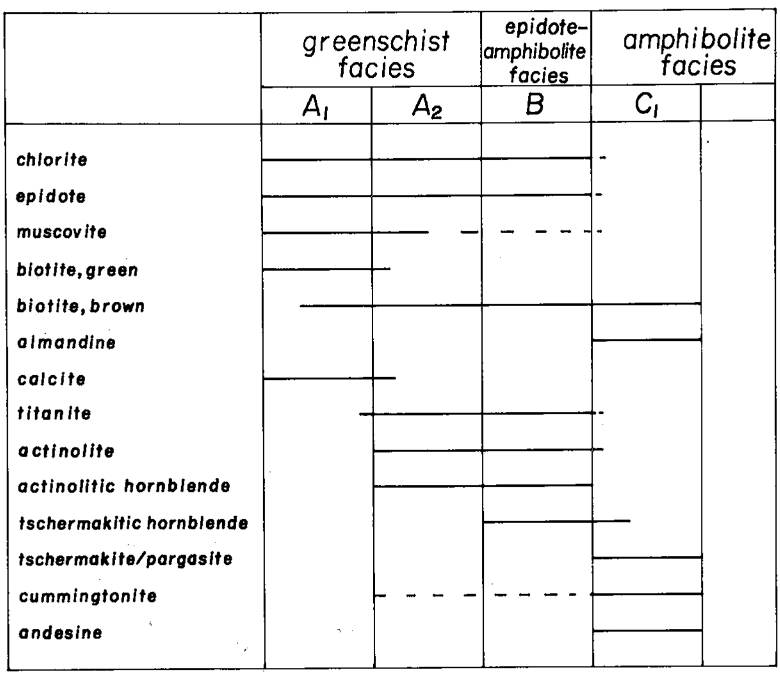

FIG. 5. Metabasite assemblages in the Sudbury Igneous Complex.

The onset of the middle- and upper-greenschist facies (A_2 zone) is marked by the appearance of actinolite and the disequilibrium calcic amphibole assemblage actinolite + actinolitic hornblende ± magnesio-hornblende – ferro-edenite, along with biotite ± epidote + chlorite ± sericite ± cummingtonite + (sodic plagioclase) + quartz. This complex alteration assemblage is found at Foy, Ministic Lake, Strathcona, MacLennan, and in the Whitewater Group.

The epidote–amphibolite facies (B zone) assemblage is characterized by either coexisting actinolitic hornblende and tschermakitic hornblende or blue-green hornblende alone, along with epidote + biotite + chlorite + titanite + (oligoclase–andesine) + quartz. It is found at Kirkwood, Copper Cliff, sites 1, 3 and 6, and Creighton. At Copper Cliff locations close to the Irruptive (sites 1 and 3), calcic amphibole is subordinate to biotite.

Lower-amphibolite-facies (C_1 zone) assemblages are characterized by either dark blue-green tschermakitic hornblende or ferroan pargasite ± cummingtonite + biotite + andesine + quartz. Actinolite - actinolitic hornblende is absent, except in Mg-rich whole-rock compositions, epidote is either absent or present in minor amounts, and almandine garnet is present in the more fractionated quartz diorite (Fe-rich) compositions. This assemblage is found at Copper Cliff, site 16, Worthington, sites 7 and 10, Frood–Stobie and the Kirkwood area.

The composition of calcic amphibole is the most important indicator of metamorphic grade in altered rocks of the Sudbury Igneous Complex. We have noted above that the composition of plagioclase is not as useful in this regard as in more extensively reacted metabasite assemblages (*e.g.*, Spear 1980, 1981a) because of the incomplete reaction of plagioclase feldspar at many localities. Thomson *et al.* (1985) discussed the grade implication of the presence of blue-green calcic amphibole in metabasite terranes and reviewed supporting chemical, petrographic and experimental studies (*e.g.*, Wiseman 1934, Shido & Miyashiro 1959, Binns 1965, Graham 1974, Laird 1980, Laird & Albee 1981, Liou *et al.* 1974, Spear 1981b, Robinson *et al.* 1982, Moody *et al.* 1983, Apted & Liou 1983). It was concluded that coexisting actinolitic hornblende and aluminous hornblende correspond to the epidote–amphibolite facies and that aluminous blue-green calcic amphibole alone indicates the onset of medium-grade conditions. A similar but more elaborate subdivision of assemblages characteristic of the transition between greenschist and amphibolite facies has resulted from detailed study of the low P–T progressive metamorphism of basaltic rocks in the Yap islands, western Pacific, and in Kasuga, Japan (Maruyama *et al.* 1983). It is clear from the present study (*e.g.*, Fig. 3) and from Thomson *et al.* (1985) that the color of calcic amphibole alone is a misleading indicator of metamorphic grade, without supporting compositional data. Blue-green calcic amphibole first appears in the A_2 zone of the greenschist facies (Fig. 5) and persists through the C_1 zone of the amphibolite facies. However, in the A_2 zone this amphibole is actinolite and actinolitic hornblende, and in the C_1 zone it is tschermakitic hornblende or ferroan pargasite.

The composition of plagioclase (andesine) in the C_1 zone amphibolites of the South Range footwall and the general absence of high-pressure phases suggest that the SIC metabasites were formed under low-pressure conditions (*cf.* Robinson *et al.* 1982). This is consistent with the absence of a strong pervasive deformation in Irruptive rocks and by the general preservation of primary structures and textures in the rocks. However, from a comparative study of the ^{VI}Al content of calcic amphiboles, Fleet & Barnett (1978) concluded that the quartz diorite host rock at the Frood mine had been metamorphosed at "high" pressure. This pressure estimate is equivalent to the medium-pressure (barrovian) conditions of Laird & Albee (1981): the ^{VI}Al,^{IV}Al contents of aluminous calcic amphiboles from the Frood mine are similar to those of "hornblende" from the Hastings region, Ontario (Sampson & Fawcett 1977). Using the more elaborate ($^{VI}Al + Fe^{3+} + Ti$) *versus* ^{IV}Al plot of Laird & Albee (1981) (Fig. 4), the calcic amphiboles of the Sudbury Igneous Complex are clearly more aluminous than calcic amphiboles from the low-pressure Abukuma terrane (Shido 1958, Shido & Miyashiro 1959). They have compositions similar to those of calcic amphiboles from the medium-pressure Haast River terrane (Cooper & Lovering 1970), but have significantly lower ($^{VI}Al + Fe^{3+} + Ti$) contents than calcic amphiboles from the Dalradian (Graham 1974). We conclude, provisionally, that ambient pressures for SIC metabasites were either low or in the low to medium range.

The progressive mineral zonation presently recognized in metabasite assemblages of the Sudbury Igneous Complex is generally similar to that of low-pressure metabasite terranes, particularly those of the Shiojiri area and the central Abukuma plateau of Japan (Miyashiro 1973), northern Michigan (James 1955) and the Yap islands, western Pacific and Kasuga, Japan (Maruyama *et al.* 1983). Closest agreement exists with the Shiojiri area, if the mineral zones reported by Miyashiro (1973, Figs. 3, 4) are compared with those of Figure 5 in the following manner: Ia of Shiojiri with A_1 of the SIC, Ib with A_2, Ic and IIa with B, and IIb with C_1.

The deduction of corresponding mineral-zones in metapelites is more difficult. In northern Michigan, the biotite zone overlaps the boundary between the greenschist and epidote-amphibolite facies, and the almandine zone, which is largely in the epidote–amphibolite facies, extends into the amphibolite facies (James 1955, Miyashiro 1973). Since staurolite has been reported in xenolithic fragments within the Frood–Stobie offset (Pattison 1980), the C_1 zone (low-amphibolite facies) of the present study presumably corresponds to the upper almandine zone – lower staurolite zone of metapelites of the Southern Province. It is emphasized that the present observations suggest that the control of whole-rock composition on assemblages of metamorphic minerals in the SIC is extremely local: xenolithic inclusions are not extensively metasomatized.

Thomson *et al.* (1985) emphasized that the pervasiveness of the metamorphism of mafic rocks is very much dependent on rock permeability. Because the development of hydrous mineral assemblages requires fluid access, large, massive gabbroic bodies may exhibit only a very local response to low- and medium-grade conditions. This is particularly true where the metamorphism has occurred at a high level in the crust. Therefore, evidence of a low-pressure regional metamorphic overprint on large-volume bodies of mafic rock is easily overlooked. Pervasiveness of metamorphism clearly correlates with rock volume in the Sudbury Igneous Complex. The relatively small offset-dyke bodies in both the North and South Range footwall are more pervasively altered than adjacent Irruptive rocks.

Regional metamorphism of the Sudbury Igneous Complex

The Penokean metamorphism of northern Michigan (James 1955) and of the Southern Province in the Sudbury–Manitoulin area (Card 1978a, b) is characteristically of low-pressure type, associated with little deformation, such that primary structures and textures in the rocks are commonly preserved, and almandine garnet is absent in the almandine zone except in the more Fe-rich rocks. We have observed the same general characteristics in the postmagmatic alteration of the Sudbury Igneous Complex.

The regional distribution of metamorphic grade deduced from the metabasite assemblages of the Sudbury Igneous Complex is given in Figure 1b and compared with the metamorphic map of Card (1978a, Fig. 3) for pre- and post-Irruptive metamorphic zones in the Sudbury area. Recognizing that the upper-greenschist facies of Card (1978a, b) approximately corresponds to the epidote–amphibolite facies, and the almandine-amphibolite facies of Card corresponds to the present C_1-zone low-amphibolite facies, there exists a close agreement between the regional distribution of metamorphism of the Sudbury Igneous Complex and that of the Southern Province footwall rocks. The metamorphic zones of the Sudbury Igneous Complex are simply a mappable continuation of the nodal pattern in the Southern Province footwall.

It is clear from the present study, from that of Thomson *et al.* (1985) and from the distribution of green norite in the South Range that the isograd between the greenschist facies and the epidote-amphibolite facies must cross the Irruptive approximately in the manner indicated in Figure 1b. The isograd between the epidote-amphibolite facies and the amphibolite facies crosses the Copper Cliff offset and encloses offset rocks in the footwall at Frood–Stobie and in the Kirkwood area, and generally lies within the nodal almandine-amphibolite-facies zone of Card (1978a). This isograd also crosses the Worthington offset, in agreement with the outcrop of the almandine-amphibolite-facies zone to the southwest of the Irruptive. There appear to be abrupt local fluctuations in metamorphic grade within rocks of the Sudbury Igneous Complex adjacent to the South Range footwall contact. Since footwall metabasites indicate the same metamorphic grade as adjacent Sudbury Igneous Complex rocks at the Kirkwood mine and at the Copper Cliff and Worthington offsets, it seems most probable that similar fluctuations in grade exist in the associated metamorphosed sediments.

We have not observed subgreenschist-facies assemblages in the Sudbury Basin and, therefore, suggest that the greenschist facies extends out into the Superior Province. However, the Onwatin slate and Chelmsford grit samples examined have been metamorphosed to the chlorite zone only. Hence, there appears to be an A_1 greenschist facies – A_2 greenschist facies isograd within the Whitewater Group.

The present study confirms that the Sudbury Igneous Complex has been overprinted by an episode of low-pressure (or low- to medium- pressure) prograde metamorphism that climaxed at medium-grade conditions (low-amphibolite facies) immediately to the south of the Irruptive and faded northward. The characteristics of this metamorphism are fully consistent with those of the Penokean metamorphism of the Southern Province (Card 1978a, b) and northern Michigan (James 1955). Moreover, the distribution of metamorphic zones of the South Range and adjacent offsets is essentially identical to that of the Southern Province country rocks. Therefore, this study supports the conclusion of Brocoum & Dalziel (1974) that the metamorphism of both the Southern Province and the Sudbury Structure occurred in a single post-Irruptive, Penokean orogenic event. It is emphasized that the studies of Card (1978a, b) and Brocoum & Dalziel (1974) were restricted to rocks stratigraphically below and above the Irruptive. The Sudbury Igneous Complex itself was not examined for a regional metamorphic or deformational imprint.

We suggest that the metamorphism of the Sudbury Igneous Complex occurred shortly after its emplacement. This would be consistent with the age of the Sudbury Igneous Complex (1.84 Ga, Krogh & Davis 1974; 1.88 Ga, Hurst & Farhat 1977), the range of ages usually associated with the Penokean orogeny (1.7–1.9 Ga, Cannon 1973), and the deduced age of the Penokean orogeny in the Sudbury area (1.7–1.75 Ga, Hurst & Farhat 1977).

Thus the time of the metamorphism and deformation of the Southern Province footwall is established as post-Irruptive. This naturally places constraints on hypotheses of origin of the Sudbury Structure. Fleet (1979, 1980) reported that the conical fractures in the Southern Province footwall rocks, which had been identified by previous workers as shatter cones, were later than the main deformation (argued as post-Irruptive on the basis of the study of Fleet & Barnett 1978) and thus could not be associated with the hypothesized astrobleme event. Pattison (1980) attempted to rebut this claim by arguing that the available evidence favored a pre-Irruptive age for the metamorphism and deformation of the Southern Province footwall. Hopefully, the present study will bring this phase of the debate to an end.

Acknowledgements

We thank M.L. Thomson and INCO for access to the dyke-rock material in the Kirkwood area, and E. Sawitsky for the MacLennan samples. This study was supported by the Natural Sciences and Engineering Research Council of Canada through an operating grant to M.E. Fleet.

References

Apted, M.J. & Liou, J.G. (1983): Phase relations among greenschist, epidote–amphibolite, and amphibolite in a basaltic system. *Amer. J. Sci.* **283A**, 328-354.

Binns, R.A. (1965): The mineralogy of metamorphosed basic rocks from the Willyama Complex, Broken Hill District, New South Wales. I. Hornblendes. *Mineral. Mag.* **35**, 306-326.

Brocoum, S.J. & Dalziel, I.W.D. (1974): The Sudbury Basin, the Southern Province, the Grenville Front, and the Penokean Orogeny. *Geol. Soc. Amer. Bull.* **85**, 1571-1580.

Bussolaro, N.D. (1981): *A Petrographic Study of Mineralized Sublayer Breccia from Creighton Mine, Sudbury, Ontario.* B.Sc. thesis, Univ. Western Ontario, London, Ontario.

Cannon, W.F. (1973): The Penokean Orogeny in northern Michigan. *In* Huronian Stratigraphy and Sedimentation (G.M. Young, ed.). *Geol. Assoc. Can. Spec. Pap.* **12**, 251-271.

Card, K.D. (1964): Metamorphism in the Agnew Lake area, Sudbury District, Ontario, Canada. *Geol. Soc. Amer. Bull.* **75**, 1011-1030.

______ (1978a): Metamorphism of Middle Precambrian (Aphebian) rocks of the eastern Southern Province. *In* Metamorphism in the Canadian Shield (J.A. Fraser & W.W. Heywood, eds.). *Geol. Surv. Can. Paper* **78-10**, 269-282.

______ (1978b): Geology of the Sudbury-Manitoulin area. *Ont. Geol. Surv. Rep.* **166.**

______, Gupta, V.K., McGrath, P.H. & Grant, F.S. (1984): The Sudbury structure: its regional geological and geophysical setting. *In* The Geology and Ore Deposits of the Sudbury Structure (E.G. Pye, A.J. Naldrett & P.E. Giblin, eds.). *Ont. Geol. Surv., Spec. Vol.* **1**, 25-43.

Cooper, A.F. & Lovering, J.F. (1970): Greenschist amphiboles from Haast River, New Zealand. *Contr. Mineral. Petrology* **27**, 11-24.

Dressler, B.O. (1984a): The effects of the Sudbury event and the intrusion of the Sudbury Igneous Complex on the footwall rocks of the Sudbury structure. *In* The Geology and Ore Deposits of the Sudbury Structure (E.G. Pye, A.J. Naldrett & P.E. Giblin, eds.). *Ont. Geol. Surv., Spec. Vol.* **1**, 97-136.

______ (1984b): General geology of the Sudbury area. *In* The Geology and Ore Deposits of the Sudbury Structure (E.G. Pye, A.J. Naldrett & P.E. Giblin, eds.). *Ont. Geol. Surv., Spec. Vol.* **1**, 57-82.

Ferry, J.M. (1985): Hydrothermal alteration of Tertiary igneous rocks from the Isle of Skye, northwest Scotland. *Contr. Mineral. Petrology* **91**, 264-282.

Fleet, M.E. (1979): Tectonic origin for Sudbury, Ontario, shatter cones. *Geol. Soc. Amer. Bull.* **90**, 1177-1182.

______ (1980): Tectonic origin for Sudbury, Ontario, shatter cones: reply. *Geol. Soc. Amer. Bull.* **91**, 755-756.

______ & Barnett, R.L. (1978): Al^{IV}/Al^{VI} partitioning in calciferous amphiboles from the Frood mine, Sudbury, Ontario. *Can. Mineral.* **16**, 527-532.

Graham, C.M. (1974): Metabasite amphiboles of the Scottish Dalradian. *Contr. Mineral. Petrology* **47**, 165-185.

Grapes, R.H. & Graham, C.M. (1978): The actinolite–hornblende series in metabasites and the so-called miscibility gap: a review. *Lithos* **11**, 85-97.

Guy-Bray, J.V., ed. (1972): New developments in Sudbury geology. *Geol. Assoc. Can., Spec. Pap.* **10.**

Hawthorne, F.C. (1981): Amphibole spectroscopy. *In* Amphiboles and Other Hydrous Pyriboles – Mineralogy (D.R. Veblen, ed.). *Mineral. Soc. Amer., Rev. Mineral.* **9A**, 103-139.

______ (1983): The crystal chemistry of the amphiboles. *Can. Mineral.* **21**, 173-480.

______ & GRUNDY, H.D. (1973): The crystal chemistry of the amphiboles. I. Refinement of the crystal structure of ferrotschermakite. *Mineral. Mag.* **39**, 36-48.

HURST, R.W. & FARHAT, J. (1977): Geochronologic investigations of the Sudbury Nickel Irruptive and the Superior Province granites north of Sudbury. *Geochim. Cosmochim. Acta* **41**, 1803-1815.

JAMES, H.L. (1955): Zones of regional metamorphism in the Precambrian of northern Michigan. *Geol. Soc. Amer. Bull.* **66**, 1455-1488.

KROGH, T.E. & DAVIS, G.L. (1974): The age of the Sudbury Nickel Irruptive. *Carnegie Inst. Wash. Year Book* **73**, 567-569.

LAIRD, J. (1980): Phase equilibria in mafic schist from Vermont. *J. Petrology* **21**, 1-37.

______ & ALBEE, A.L. (1981): Pressure, temperature, and time indicators in mafic schist: their application to reconstructing the polymetamorphic history of Vermont. *Amer. J. Sci.* **281**, 127-175.

LEAKE, B.E. (1978): Nomenclature of amphiboles. *Can. Mineral.* **16**, 501-520.

LIOU, J.G., KUNIYOSHI, S. & ITO, K. (1974): Experimental studies of the phase relations between greenschist and amphibolite in a basaltic system. *Amer. J. Sci.* **274**, 613-632.

MARUYAMA, S., SUZUKI, K. & LIOU, J.G. (1983): Greenschist–amphibolite transition equilibria at low pressures. *J. Petrology* **24**, 583-604.

MIYASHIRO, A. (1973): *Metamorphism and Metamorphic Belts.* Allen & Unwin, London.

MOODY, J.B., MEYER, D. & JENKINS, J.E. (1983): Experimental characterization of the greenschist/amphibolite boundary in mafic systems. *Amer. J. Sci.* **283**, 48-92.

MORRIS, W.A. (1982): A paleomagnetic investigation of the Sudbury basin offsets, Ontario, Canada. *Tectonophys.* **85**, 291-312.

NALDRETT, A.J., BRAY, J.G., GASPARRINI, E.L., PODOLSKY, T. & RUCKLIDGE, J.C. (1970): Cryptic variation and the petrology of the Sudbury Nickel Irruptive. *Econ. Geol.* **65**, 122-155.

PALMER, H.C., MERZ, B.A. & HAYATSU, A. (1977): The Sudbury dikes of the Grenville Front region: paleomagnetism, petrochemistry, and K–Ar age studies. *Can. J. Earth Sci.* **14**, 1867-1887.

PAPIKE, J.J., CAMERON, K.L. & BALDWIN, K. (1974): Amphiboles and pyroxenes: characterization of *other* than quadrilateral components and estimates of ferric iron from microprobe data. *Geol. Soc. Amer., Abstr. Programs* **6**, 1053-1054.

PATTISON, E.F. (1979): The Sudbury sublayer. *Can. Mineral.* **17**, 257-274.

______ (1980): Tectonic origin for Sudbury, Ontario, shatter cones: discussion. *Geol. Soc. Amer. Bull.* **91**, 754-755.

PYE, E.G., NALDRETT, A.J. & GIBLIN, P.E., eds. (1984): The Geology and Ore Deposits of the Sudbury Structure. *Ont. Geol. Surv., Spec. Vol.* **1**.

ROBINSON, P., SPEAR, F.S., SCHUMACHER, J.C., LAIRD, J., KLEIN, C., EVANS, B.W. & DOOLAN, B.L. (1982): Phase relations of metamorphic amphiboles: natural occurrence and theory. *In* Amphiboles: Petrology and Experimental Phase Relations (D.R. Veblen & P.H. Ribbe, eds.). *Mineral. Soc. Amer., Rev. Mineral.* **9B**, 1-227.

SAMPSON, G.A. & FAWCETT, J.J. (1977): Coexisting amphiboles from the Hastings region of southeastern Ontario. *Can. Mineral.* **15**, 283-296.

SHIDO, F. (1958): Plutonic and metamorphic rocks of the Nakoso and Iritono districts in the central Abukuma Plateau. *J. Fac. Univ. Tokyo* II, **11**, 131-217.

______ & MIYASHIRO, A. (1959): Hornblendes of basic metamorphic rocks. *J. Fac. Univ. Tokyo* II, **12**, 85-102.

SOUCH, B.E., PODOLSKY, T. & GEOLOGICAL STAFF (1969): The sulfide ores of Sudbury: their particular relationship to a distinctive inclusion-bearing facies of the nickel irruptive. *In* Magmatic Ore Deposits (H.D.B. Wilson, ed.). *Econ. Geol., Mon.* **4**, 252-261.

SPEAR, F.S. (1980): NaSi ⇌ CaAl exchange equilibrium between plagioclase and amphibole: an empirical model. *Contr. Mineral. Petrology* **72**, 33-41.

______ (1981a): Amphibole–plagioclase equilibria: an empirical model for the relation albite + tremolite = edenite + 4 quartz. *Contr. Mineral. Petrology* **77**, 355-364.

______ (1981b): An experimental study of hornblende stability and compositional variability in amphibolite. *Amer. J. Sci.* **281**, 697-734.

THOMSON, M.L., BARNETT, R.L., FLEET, M.E. & KERRICH, R. (1985): Metamorphic assemblages in the South-Range norite and footwall mafic rocks near the Kirkwood mine, Sudbury, Ontario. *Can. Mineral.* **23**, 173-186.

WISEMAN, J.D.H. (1934): The central and south-west Highland epidiorites: a study in progressive metamorphism. *Quart. J. Geol. Soc. London* **90**, 354-417.

Received March 18, 1986, revised manuscript accepted November 1, 1986.