Canadian Mineralogist
Vol. 24, pp. 747-759 (1986)

FELDSPAR MINERALOGY OF THE SUDBURY IGNEOUS COMPLEX AND THE ONAPING FORMATION, SUDBURY, ONTARIO

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ABSTRACT

The mineralogy of the feldspars in the Sudbury Igneous Complex and overlying tuffs of the Onaping Formation places constraints on the geological evolution of the Sudbury Basin in Ontario. In the gabbroic part of the complex, the magmatic plagioclase has become ordered, and commonly albitized. Albitization becomes pervasive near the top of the gabbro. The interstitial K-feldspar is well-ordered microcline. Granophyre contains albite (An_0 - An_2), also the product of albitization of a plagioclase richer in Ca. Microcline in the granophyre is partly disordered. The Onaping tuffs are compositionally zoned, from Na-rich at the base to potassic at the top; the zonation reflects ion-exchange phenomena during cooling of the ignimbritic sheet. Albite in the tuffs is almost pure and ordered, and K-feldspar is poorly ordered microcline or orthoclase. The metamorphic overprint was too mild to remove these metastable phases. The entire suite (the complex and the Onaping Formation) may have cooled as a single unit. The thoroughness of the subsolidus changes in the Onaping tuffs suggests that the Onaping melt was everywhere at or near saturation in water. This state would seem to rule out an origin of these melts by meteoritic impact.

Keywords: Sudbury Igneous Complex, Onaping tuffs, plagioclase, albitization, microcline, orthoclase, Al-Si order, ion exchange, Ontario.

SOMMAIRE

La minéralogie des feldspaths du complexe igné de Sudbury et de la nappe de tufs de la formation Onaping permet de préciser l'évolution géologique du bassin de Sudbury (Ontario). Dans la partie gabbroïque du complexe, le plagioclase primaire est devenu ordonné, et il est couramment albitisé. L'albitisation est répandue dans la partie supérieure du niveau gabbroïque. Le feldspar potassique interstitiel est un microcline ordonné. Le granophyre contient une albite (An_0 - An_2), produit de l'albitisation d'un plagioclase plus riche en Ca. Le microcline est partiellement désordonné. Les tufs de la formation Onaping sont zonés (sodiques à la base, potassiques au haut de la section), ce qui refléterait un phénomène d'échange d'ions pendant le refroidissement de la nappe ignimbritique. L'albite y est quasiment pure et ordonnée, et le feldspath potassique est un microcline relativement désordonné ou une orthose. Le réchauffement métamorphique postérieur a été trop faible pour éliminer ces phases métastables. La suite au complet (le complexe de Sudbury et les tufs de la formation Onaping) pourrait avoir refroidi en même temps. La portée des transformations dans les tufs fait penser que le magma était soit saturé en eau, soit près de son point de saturation. Cette condition semble écarter une origine par impact météoritique pour ce magma.

Mots-clés: complexe igné de Sudbury, tufs de la formation Onaping, plagioclase, albitisation, microcline, orthose, degré d'ordre Al-Si, échange d'ions, Ontario.

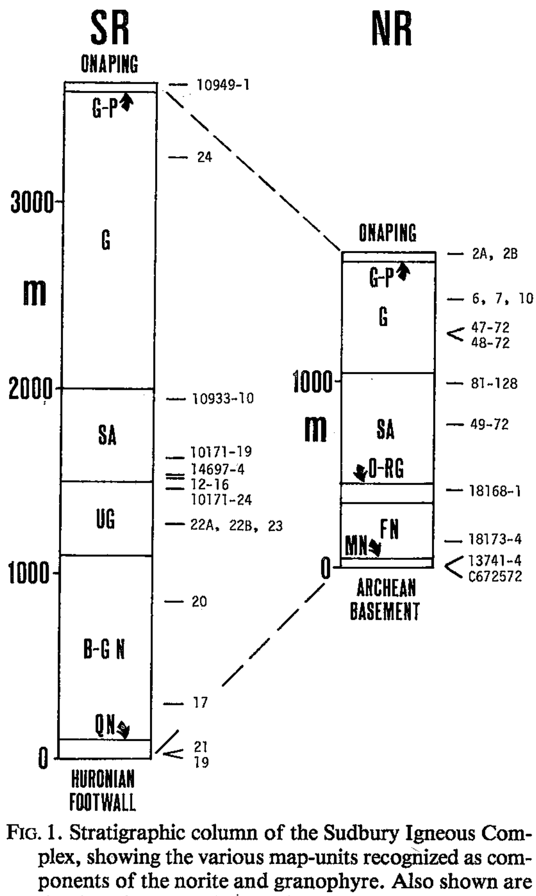

FIG. 1. Stratigraphic column of the Sudbury Igneous Complex, showing the various map-units recognized as components of the norite and granophyre. Also shown are the locations of the specimens selected for study. Abbreviations: SR South Range, NR North Range, QN quartz norite, B-GN black - green norite, UG upper gabbro, SA salmon granophyre, G grey granophyre, G-P granophyre relatively poor in granophyrically intergrown material, MN mafic norite, FN felsic norite, O-RG oxide-rich gabbro. Thickness expressed in metres. The sequence of samples (numbers in light type) is that followed in Tables 1 and 4.

INTRODUCTION

The geological evolution of the Sudbury Basin has been the subject of debate (Guy-Bray 1972, Pye *et al.* 1984). Whereas some of its features are well described, the data base for others is not adequate. We characterize here, in quantitative terms, the feldspar mineralogy of the Sudbury Igneous Complex and of the overlying Onaping Formation. These data provide constraints on the geological evolution of the Sudbury Basin.

The Sudbury Igneous Complex, emplaced approximately 1850 Ma ago (Krogh *et al.* 1982, 1984), occurs as an ENE-trending elliptical ring 27 km wide and 60 km long. It consists of an inwardly dipping composite sill of coeval norite and granophyre. Vertically gradational units can be followed around the Basin. Generalized stratigraphic sections are presented for the South and North Ranges in Figure 1.

The Onaping Formation overlies and is intruded by the Sudbury Igneous Complex. It was emplaced

TABLE 1. LOCATION AND PETROGRAPHY OF THE SPECIMENS SELECTED FOR STUDY (LISTED IN STRATIGRAPHIC SEQUENCE, FIGS. 1, 6)

Black tuff			
44-73A	small frags, white lava in bl tf	centre E side L 10, C V, Capreol* NR	v.f.g. tabular fs (all orthoclase: Table 4); frag qtz xls; metacrystic carbonate
44-73B	silty bl tf mx	same as for 44-73A	pect pum lap, large shards, frags amyg lava, chert, broken qtz xls, tr. pl, mc grains, all in fol f.g. bl mx c.p. small shards; pum & shards carbonatized
13094-1	thin lens gy amyg lava in bl tf	SW¼, L 1, C VI, Blezard SR	m.g. felted laths, mesostasis rich in Kfs; minor amyg qtz, scattered chl, actin & bi
16156-4	long lens gy spher. lava in bl tf	SE¼, L 2, C I, Wisner NR	c.p. spherulites, small areas of v.v.f.g. fs fibres in larger areas radial laths; interspher. chl, amyg. qtz
16155-3	bl tf	SE¼, L 2, C I, Wisner NR	pect pum lap, shards, broken qtz, ab xls all in bl v.f.g. mx c.p. shards. Chl & actin in pum
16146-5C	frag flinty gn "rhy" (welded rhy tf) in bl	SW¼, L 1, C I, Wisner NR	c.p. barely distinguishable shards of v.f.g. ab; small frag swirly lava like 44-73A; frags qtz xls; amyg qtz
13307-3	bl tf	SW¼, L 8, C IV, Dowling NR	c.p. pect pum lap, shards, broken qtz xls in bl f.g. mx of v.f.g. shards; pum & shards tabular; tr. titanite
5	bl tf	centre L 8, C IV, Dowling	no thin section
5A	bl tf	same as for 5	c.p. pect pum lap & shards in bl mx; barely resolvable shards; platy ab in lap, shards, frags qtz xls, chert
10940-7	lens gy spher. lava in bl tf	NE¼, L 9, C VI, Snider SR	single lath & bow-tie to spherulitic pl, int. gphr, m.g.; qtz amyg; overall f.g. bi
10941-1	lava mx of qte boulder lens in bl tf	NE¼, L 9, C VI, Snider SR	oval frags of mosaic qte, qtz fringed by qtz laths after tridymite; mx v.v.f.g.
2-72	qte pebble in lava mx in bl tf	NE¼, L 11, C I, Norman NR	qte in lava mx; qtz frags fringed by qtz laths after tridymite; in mx, plumes of ab fibres
31-73	bl tf	E side, centre, L 11, C I, Norman NR	pect pum lap, shards, broken qtz xls, tr. rounded mc, pl & qtz, lava frags, all in bl mx
13092-2	long lens gy amyg lava in bl tf	SE¼, L 1, C VI, Blezard SR	mosaic qtz amyg in mx c.p. spherulites of blades and fibres of ab; granular ep, f.g. chl, actin blades
Grey tuff			
12-73	gy tf	centre E side L 8, C VI, Capreol NR	v.c.p. pect pum lap & shards in mx small shards, frags qtz xls; pum & shards recryst ab; actin-, chl-filled "vesicles", much actin in groundmass
28-72A	qte pebble in gy tf	SW¼, L 10, C II, Norman NR	fractured xls granular qtz in f.g. crush mx of qtz & ab
28-72B	gy tf mx for 28-72A	same as for 28-72A	v.c.p. pect pum lap, shards & frags qtz xls, all in f.g. mx c.p. small shards; pum & shards largely recryst ab; much f.g. actin overall
19-72	lens banded flinty gn "rhy" in gy tf	centre L 10, C II, Norman NR	lenticles & bands f.g. felted laths ab destroying outlines of v.c.p. small shards; frags qtz xls; qtz amyg; v.f.g. actin overall; welded rhy tf
15477-5	lens banded flinty gn "rhy" in gy tf	same as for 19-72	v.c.p. distinguishable shards of needle ab; patches plumose fibres ab; frags qtz xls; amyg qtz; tr. euhedral ab, actin overall; highly welded rhy tf
22-72	lens banded flinty gn "rhy" in gy tf	same as for 19-72	v.f.g. ab in c.p. distinct shards; tr. recryst pum lap; frags qtz xls, qtz amyg; v.f.g. actin overall; highly welded rhy tf
26-72	frag Creighton gran in lens gn tf in gy	same as for 19-72	slightly crushed c.g. ab, qtz; some ab chessboard; some patches Kfs, tr. stilpnomelane
15478-5	lens of pink-frag albitized gn tf	same as for 19-72	c.p. pink, pect pum lap in mx f.g. shards, lap c.g. ab much of it chessboard, shards f.g. ab; widespread actin; metacrystic hbl, tr. titanite in lap
43-72	lens albitized qte at base of gy tf	NE¼, L 8, C VI, Capreol NR	mortared qtz & chessboard ab in mx of crushed ab, mainly
33-72	qte block at base of gy tf	same as for 43-72	plumose fibre ab as mx & replacing frags of qte fringed by qtz laths after tridymite
2C	"gy Onaping"? or uppermost mpeg	centre L 8, C IV, Dowling NR	no thin section
2C incl.	altered granitic inclusion in 2C	same as for 2C	no thin section

Granophyre, South Range			
10949-1	foliated upper grey granophyre	east L 3, C III, Creighton	porphyroclasts of An_5, adhering f.g. gphr, f.g. recryst. matrix of qtz, Kfs(?), bt
24	grey granophyre	centre, L 7, C IV, Blezard, 500 m S Onaping cont.	very cataclastic, clasts of pl An_8, adhering gphr, f.g. matrix of qtz, bt
10933-10	felsic salmon granophyre	SE¼, L 10, C V, Snider, 700 m N nor contact	clear pl An_5 replaced by chessboard An_5, itself replaced by Kfs, c.g. gphr (qtz + pl)
10171-19	felsic salmon granophyre	NE¼, L 5, C VI, Denison 200 m N nor contact	cataclastic, chessboard An_5 in sunburst gphr, recryst. matrix rich in qtz
14697-4	mafic salmon gneissic granophyre	L 10, C II, Creighton, 15 m N nor contact	abundant sunburst gphr on euhedral pl An_5, chessboard An_5 extensively replaced by Kfs
12	oval f.g. felsic inclusion	centre, L 3, C I, Rayside, close to upper gabbro	no thin section
13	patch of f.g. felsite	same as for 12	no thin section
14	patch of f.g. felsite	same as for 12	no thin section
15	patch of f.g. felsite	same as for 12	no thin section
16	patch of f.g. felsite	same as for 12	mosaic qtz, pl An_6, some K-metasomatized. Tartan mc
Granophyre, North Range			
2B	uppermost grey granophyre	centre, L 8, C IV, Dowling, contact with Onaping	recryst. An_5 + qtz in matrix of An_5 laths and f.g. gphr; qtz after tridymite
2A	uppermost grey granophyre	same as for 2B	laths of An_1 in matrix of stouter An_5, all in f.g. gphr; qtz after tridymite
6	grey granophyre	NE¼, L 9, C IV, Dowling, 300 m NE Onaping contact	no thin section
7	grey granophyre	same as for 6; railway cut	no thin section
10	grey granophyre	same as for 6	pl An_5 in relatively f.g. gphr; xenocrystic qtz
47-72	grey granophyre	NE¼, L 7, C VI, Capreol, 600 m NE Onaping contact	long pl laths An_3 in gphr; chessboard ab is K-metasomatized. Stilpnomelane noted
48-72	grey granophyre	same as for 47-72	long pl laths An_1 in gphr; chessboard ab is K-metasomatized
81-128	felsic patch in salmon granophyre	S L 10, C V, Dowling,	m.g. recryst. qtz, tartan mc, pl An_7, in part K-metasomatized
49-72	salmon granophyre	NE¼, L 6, C VI, Capreol, 500 m SW nor contact	c.g. sunburst gphr around clear pl An_1. Chessboard ab K-metasomatized
Norite and upper gabbro, South Range			
10171-24	upper gabbro	centre, L 5, C VI, Denison, 50 m S nor-gy contact	pl m.g., sl. zoned, An_{45}, int. gphr containing K-metasomatized chessboard ab
22A	upper gabbro	centre, L 5, C III, Blezard, 400 m S nor-gy cont.	pl c.g., altered, An_{45}, prominent ep, abundant gphr, sl. K-metasomatized chessboard ab
22B	sheared aplite	same as for 22A	pl m.g., An_5, some normal and clear, some chessboard and turbid
23	upper gabbro	same as for 22A	fresher pl than in 22A, zoned, core An_{60}, rim An_{55}.
23Gr	granitic patch	same as for 22A	no thin section
20	black norite	SE¼, L 5, C III, Blezard, 1.3 km N nor-ftwl contact	no thin section
17	green norite	SW¼, L 11, C VI, McKim, Hwy 144, 0.5 km N nor-ftwl	fresh pl, strongly zoned, core An_{65}, rim An_{20}, no gphr, no mc, int. qtz
21	black-brown norite	centre, L 4, C II, Blezard, Hwy 69, near basal contact	fresh pl, zoned, core An_{65}, rim An_{60}, int. qtz, mc, no gphr; pyroxene fresh
19	amphibolite in 21	same as for 21	minor pl An_{65} + qtz + blue-green hbl
Norite and oxide-rich gabbro, North Range			
18168-1	oxide-rich gabbro	S L 6, C II, Bowell, 50 m N mpeg contact	pl finer, more lath-shaped than in norite; remnants of An_{32}; abundant gphr around pl
18173-4	felsic norite	NE¼, L 5, C II, Bowell, 125 m S nor-ftwl contact, base of Foy offset	pl An_{64} mostly fresh, gphr contains K-metasomatized chessboard ab
13741-4	mafic norite	L 2, C V-VI, Capreol, E Capre L., near ftwl contact	pl An_{68} m.g., unaltered, minor int. gphr
C672572-1	mafic norite	SW¼, L 10, C I, Bowell, at very base of mafic norite	pl An_{58}, laths intensely altered, f.g. tartan mc; gphr
C672572-2	felsic inclusion	same as for C672572-1	

Abbreviations: L lot, C concession, bl tf black tuff, gy tf grey tuff, nor norite, gp granophyre, ftwl footwall, rhy rhyolite, v. very, f.g. fine-grained, m.g. medium-grained, c.g. coarse-grained, gn green, tr. trace, sl. slightly, int. interstitial, frag fragment, incl. inclusion, xls crystals, recryst. recrystallized, pect pectinate, lap lapilli, pum pumice, ab albite, actin actinolite, bi biotite, chl chlorite, ep epidote, fs feldspar, hbl hornblende, Kfs K-feldspar, mc microcline, pl plagioclase, qte quartzite, qtz quartz, spher. spherulitic, cont. contact, gphr granophyric intergrowth of quartz and feldspar. * Name of township. Petrographic descriptions of the Onaping black and grey tuffs, lava fragments and welded tuffs focus on texture of the specimen and on habit of the feldspar grains, which are relevant to the identification of lithology in the Onaping. Petrographic descriptions of the granophyre and norite specimens focus on the state of the K-rich feldspar and textural and compositional properties of plagioclase; the composition of the plagioclase is inferred from the extinction angle (Michel-Levy method). The order followed in this listing is the same as adopted in Figures 1 and 6 and in Table 4. For convenience, granophyre and norite specimens are listed separately for the North and South Ranges.

explosively 1836 ± 14 Ma ago (Krogh *et al.* 1984). Its basal member, a quartzite breccia (Stevenson 1961), is overlain by a lower grey tuff and an upper black tuff member (Muir & Peredery 1984). Lenses of pink-fragment-bearing green tuff occur near the base of the grey tuff. The black tuff contains disseminated carbonaceous material; the grey tuff lacks this constituent. The green tuff is characterized by widespread, finely disseminated actinolite. The tuffs contain 1) pumice lapilli and shards (Stevenson 1972) and fragments of devitrified glass (Peredery 1972), and 2) lithic fragments, mainly quartzite and felsic to mafic volcanic rocks similar to those encountered in the footwall of the norite.

The rocks found in the North Range are less deformed, less steeply tilted and more pristine than South-Range equivalents, which were affected by the Penokean (Brocoum & Dalziel 1974) or Hudsonian orogeny, and later by the Grenville event (Card 1978, p. 280).

Our objectives here are 1) to characterize the feldspar assemblage of representative specimens (Table 1) and 2) to evaluate the implications of horizontal and vertical gradients in the feldspar mineralogy of these units. Unit-cell parameters of the feldspars provide information on the composition and degree of Al–Si order. Plagioclase compositions were routinely determined using the Michel–Lévy method and checked by electron microprobe in a few cases.

Techniques of Microsampling and Determination of the Cell Constants

Millimetre-size grains of feldspar were hand-picked and X-rayed. Any xenolith or distinctive feature was sampled separately. Aphanitic specimens were pulverized, and the whole rock was X-rayed. The cell parameters were refined by least squares using indexed diffraction-maxima [Guinier–Hägg focusing camera, Cu$K\alpha_1$ radiation, synthetic spinel internal standard ($a = 8.0833$ Å at room temperature)] and the program of Appleman & Evans (1973). This approach provides information on the dominant feldspar in the small (~ 1 mm^3) sample.

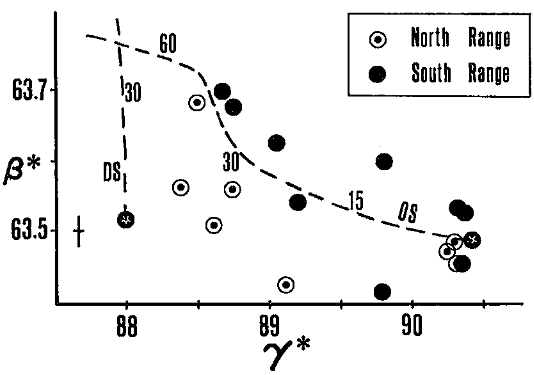

FIG. 2. Plot of β^* *versus* γ^* (in degrees) of the plagioclase in norite and mafic footwall. Two curves are shown, one for ordered structures (labeled OS), the other for disordered structures (DS). The location of calcium-free albite (OS and DS) is shown by an encircled star. Representative An contents are shown along each curve. An average error-bar is plotted in the lower left corner. The full diagram is provided by Smith (1974, Fig. 7–44).

Feldspar Mineralogy of the Basic Rocks

Previous work and petrographic details

Naldrett *et al.* (1970) stated that the composition of plagioclase in the norite varies cryptically as a function of stratigraphic height. A progressive decrease in An content, from An_{65} to An_{50}, was found from the base toward the top of the noritic layer in the North Range (electron-microprobe data; maximum difference between core and rim: 7% An). In the South Range, a similar decrease occurs from the quartz-rich norite (An_{62}–An_{65}) through the interval of black norite to the upper gabbro (An_{45}–An_{50}). The plagioclase changes abruptly to An_1–An_5 in the upper part of the oxide-rich gabbro (North Range) and upper gabbro (South Range). Davis & Slemmons (1962) described the plagioclase, in the range An_{55} to An_{65}, as highly ordered, on the basis of the 131 indicator (powder diffractometry). Naldrett *et al.* (1970) and Scribbins *et al.* (1984) proposed that the cryptic variation in the composition of plagioclase (and the pyroxenes), as well as the development of a cumulus texture near the base, constitute diagnostic signs that fractional crystallization occurred in a reservoir of basic magma.

Of the 17 specimens of mafic lithologies examined, 14 are samples of South- and North-Range norite (Fig. 1, Table 1). The suite shows signs of deuteric alteration or metamorphic recrystallization to varying degrees. The most pristine specimens are black mafic norite, as illustrated respectively by specimens 21, from the lower unit in the South Range, and 13741-4, from the base of the norite in the eastern part of the North Range. The black norite consists predominantly of zoned plagioclase, hypersthene, inverted pigeonite and biotite. Small amounts of interstitial granophyre and cross-hatched microcline are present.

In the upper gabbro in the South Range and the oxide-rich gabbro in the North Range, the plagioclase is extensively saussuritized. The presence of disseminated epidote suggests an originally more calcic plagioclase.

The composition and degree of order of the plagioclase

The plagioclase in norite typically is zoned. Electron-microprobe data were obtained for a black norite (21) from near the base of the section of Blezard Township (South Range), and a green norite (17) collected roughly 150 m up the section in McKim Township (South Range). The core of the plagioclase in the black norite ranges from An_{64} to An_{54}, whereas the rim ranges from An_{53} to An_{41}. The composition of the core agrees well with the data reported by Naldrett *et al.* (1970, Fig. 18). Plagioclase in the green norite has a core of similar composition (An_{58} to An_{56}), but the rim reaches An_{25}, which is considerably more sodic than the rim compositions reported by Naldrett *et al.* (1970). The transition in color from areas of black norite to areas of enveloping green norite reflects the appearance of amphibole + quartz at the expense of the primary pyroxenes. This transformation is accompanied by the breakdown of the primary plagioclase to a more sodic composition.

An approach based on X-ray diffraction necessarily provides information on the dominant geometry of the unit cell in a 1-mm^3 sample. This geometry is a function of An content *and* degree of order of Al and Si. The β^* - γ^* plot is used to separate these two variables in sodic plagioclase (Smith 1974). The cell-dimension data are listed in Table 2, available from the Depository of Unpublished Data, CISTI, National Research Council, Ottawa, Ontario K1A 0S2.

In most samples, the plagioclase plots close to the line marking the locus of ordered structures (Fig. 2). This is to be expected of plagioclase in a plutonic complex. Some samples are displaced along poorly defined isopleths toward the locus of disordered structures, expected in rapidly quenched systems. The samples that seem the most disordered are 23, 28, 30, 13741–4 and 18173–4. Note that 28 and 30 are taken from the footwall of the norite, and 18173–4 and 13741–4 are felsic and mafic norite, respectively, all from the North Range. Some specimens plot slightly beyond (above) the ordered plagioclase curve, but not significantly in view of the standard error in β^* (Fig. 2).

The plagioclase in the specimens ranges from An_{50} to An_0 (Fig. 2). Three specimens contain plagioclase close to the original composition: 20 and 21 are black norite from the South Range (Blezard section), and 27 is mafic footwall from the North Range. All other samples contain plagioclase that has a "disturbed" composition. Six specimens out of the 17, from the upper part of the gabbroic unit and from both flanks of the Basin, contain pure albite as the dominant plagioclase, as expected in rocks equilibrated in the greenschist facies. Although relics of more calcic plagioclase can be recognized, the abundance of chessboard albite and epidote indicates extensive albitization.

Discussion

The compositional profiles of Naldrett *et al.* (1970, Figs. 16, 17A, B, 18A, B, 19) suggest that in the noritic units, the plagioclase varies systematically upward in composition, and is thus a reliable primary phase on which to map the cryptic layering said to characterize the complex. Our data are not quite as reassuring: the noritic portion of the complex seems considerably more variable than previously considered. The plagioclase has been transformed from its primary composition in many cases; in 6 specimens out of 17, all from the upper part of the gabbroic unit, the reaction has gone to completion. Whereas we do not dispute that cryptic layering exists in the Sudbury Igneous Complex, we contend that the evidence for this working hypothesis must rest on the compositional variations in the orthopyroxene and clinopyroxene; pertinent data on these phases were provided by Naldrett *et al.* (1970). The pyroxenes are known to be much less reactive than plagioclase during the subsolidus evolution of a typical stratiform plutonic complex.

In the system Ab - An at low to moderate pressures (*e.g.*, Smith 1974, Moody *et al.* 1985), pure albite is the plagioclase that stably coexists with a calcic mineral like epidote below 400°C. A more calcic plagioclase is metastable. The albitization reac-

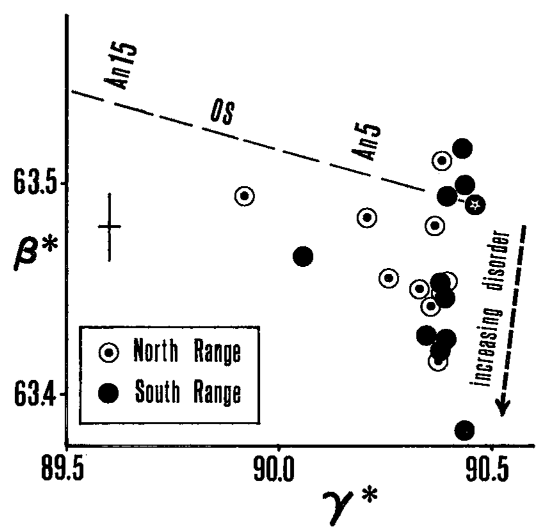

FIG. 3. Plot of β^* *versus* γ^* (in degrees) of the plagioclase in granophyre. This figure is an expanded version of Figure 2; OS refers to the locus of ordered structures. An average error-bar is plotted along the left-hand side. Ordered pure albite: encircled star.

tion consumes water; the distribution of water in the noritic portion of the complex may have been variable. The occurrence of microcline inferred to be well ordered (in view of its coarse grid pattern of twinned domains) as an accessory interstitial mineral in norite also suggests the importance of thorough subsolidus transformations in the presence of a hydrous phase.

Whether or not large-scale zones exist where the magmatic plagioclase has been completely converted to pure albite, either because of a greater flux of fluid at the deuteric stage or because of locally more intense deformation during an episode of regional metamorphism, cannot be answered yet. Distinctions between North- and South-Range rocks also are difficult to establish with confidence. There is a hint that in the North Range, the plagioclase is more likely to be compositionally transformed, though less well ordered, than in the South Range, where norites are more likely to contain patches of well-ordered andesine or labradorite. None of the samples of norite selected for study contains the competely disordered plagioclase that originally crystallized from the basic magma.

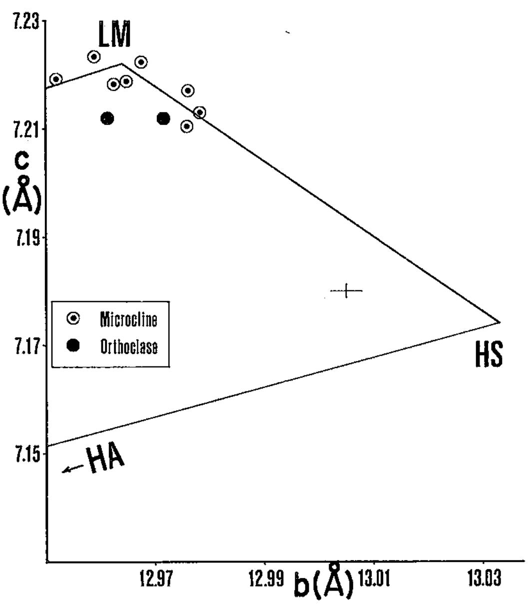

FIG. 4. Plot of the cell edges *b versus c* for the K-feldspar found in granophyre. The microcline data-points are scattered rather than clustered near the low microcline corner of the quadrilateral, indicating a significant degree of Al–Si disorder. An average error-bar is plotted near the high sanidine corner. Symbols: LM low microcline, HS high sanidine, HA high albite. The coordinates of the end members are those of Kroll & Ribbe (1983, Table 4).

FELDSPAR MINERALOGY OF THE GRANOPHYRE

Previous work and petrographic details

Little has been done on the feldspar mineralogy of the granophyre member. The modal differences in the feldspars have been noted in general by Stevenson & Colgrove (1968) and in detail by Peredery & Naldrett (1975). The pattern of distribution noted is not compatible with progressive fractional crystallization of the complex from a single basic magma.

In spite of the modal differences noted, the composition of the plagioclase is surprisingly homogeneous across the granophyre (less than 4% An and 1% Or). Davis & Slemmons (1962) found seven samples studied optically to contain An_{13} – An_{15} (North Range) and An_{22} – An_{33} (South Range). These ranges are significantly more calcic than those reported by Naldrett and coworkers and by us. The plagioclase in most samples appears to be structurally intermediate (*i.e.*, less well ordered than plagioclase in the subjacent norite).

Plagioclase

The granophyre and its felsic inclusions contain albite ranging from An_0 to An_2; 16 out of 20 data points plot in this interval (Fig. 3; Table 3, available from the Depository of Unpublished Data, CISTI, National Research Council, Ottawa, Ontario K1A 0S2). Note that of the four samples containing plagioclase more calcic than An_2 (maximum: An_{10}), three come from the North Range. Many data points (Fig. 3) depart from the locus of ordered plagioclase in the direction of decreasing β^*, indicating the presence of slight Al–Si disorder. Martin (1984) documented such departures from the ordered curve, apparently increasing with decreasing An content, in albitized plagioclase from an ophiolitic complex in the Western Alps. The disorder is considered "residual"; it reflects the distribution of aluminum in a more Ca- and Al-rich primary plagioclase. The distribution of points thus supports the working hypothesis of Naldrett *et al.* (1970), that the plagioclase is now more sodic than it once was.

K-feldspar

Only 13 of the 20 samples from the granophyre unit contain sufficient K-feldspar to allow unit-cell refinement. In most samples, the K-feldspar is microcline, but it generally is not well ordered; there is considerable scatter among samples (Table 3, Fig. 4), unlike the uniformity typical of plutonic rocks of comparable age. The calculated value of t_1O, the proportion of Al in the T_1O position, ranges from 0.85 to 1 (Table 4). In well-ordered microcline, t_1O equals 1; values of less than 0.92 characterize struc-

TABLE 4. INDICATORS OF COMPOSITION AND DEGREE OF Al-Si ORDER FOR FELDSPARS OF THE SUDBURY IGNEOUS COMPLEX AND THE ONAPING TUFFS

A. Plagioclase	β^*	γ^*	$\Delta 131$	An
44-73B NR BT	63.540	90.377	1.027	1
13094-1 SR BT lava	63.549	90.364	1.123	2
16155-3 NR BT	63.541	90.307	1.145	3
16146-5C NR BT rhy incl.	63.417	90.436	1.040	0
13307-3 NR BT	63.539	90.394	1.110	2
5A NR BT	63.431	90.386	1.074	0
5 NR BT	63.418	90.480	1.038	0
10940-7 SR BT lava	63.541	90.390	1.143	2
10941-1 SR BT lava	63.472	90.409	1.096	0
2-72 NR BT qte	63.437	90.379	1.140	0
31-73 NR BT	63.514	90.378	1.085	1
13092-2 SR BT lava	63.455	90.252	1.104	3
12-73 NR GT	63.502	90.388	1.136	1
28-72A NR GT qte	63.503	90.415	1.080	1
28-72B NR GT matrix	63.440	90.365	1.130	0
19-72 NR GT rhy	63.512	90.341	1.131	2
15477-5 NR GT rhy	63.459	90.276	1.157	3
22-72 NR GT rhy	63.428	90.152	1.235	4
26-72 NR GT granite incl.	63.453	90.350	1.142	1
15478-5A NR GT lapilli	63.535	90.419	1.118	1
15478-5B NR GT rim	63.491	90.398	1.107	1
15478-5C NR GT rim	63.462	90.362	1.133	1
15478-5D NR GT lapilli	63.515	90.395	1.128	1
43-72 NR GT qte	63.430	90.393	1.123	0
33-72 NR GT qte	63.499	90.399	1.122	1
2C NR GT or granophyre	63.486	89.910	1.270	9
2C NR felsic inclusion	63.545	90.390	1.275	2
10949-1 SR granophyre	63.453	90.385	1.133	1
24 SR granophyre	63.383	90.438	1.140	0
10933-10 SR granophyre	63.421	90.380	1.136	0
10171-19 SR granophyre	63.494	90.397	1.101	1
14697-4 SR granophyre	63.515	90.427	1.118	1
12 SR felsic inclusion	63.465	90.058	1.246	6
13 SR aplite inclusion	63.427	90.349	1.148	0
14 SR granophyre	63.446	90.387	1.152	0
15 SR aplite inclusion	63.498	90.434	1.114	1
16 SR aplite inclusion	63.426	90.392	1.117	0
2B NR granophyre	63.455	90.256	1.179	3
2A NR granophyre	63.483	90.207	1.170	5
6 NR granophyre	63.448	90.380	1.127	0
7 NR granophyre	63.450	90.330	1.115	2
10 NR granophyre	63.494	89.916	1.275	9
47-72 NR granophyre	63.511	90.383	1.132	2
48-72 NR granophyre	63.454	90.396	1.169	0
81-128 NR phenocryst	63.480	90.366	1.142	2
81-128 NR matrix	63.416	90.372	1.121	0
49-72 NR granophyre	63.442	90.357	1.137	1
10171-24 SR upper gabbro	63.533	90.347	1.131	3
22A SR norite	63.457	90.303	1.094	1
22B SR aplite inclusion	63.596	89.811	1.360	14
23 SR norite	63.415	89.792	1.263	9
23 SR felsic inclusion	63.540	89.184	1.548	20
20 SR brown norite	63.696	88.670	1.733	45
17 SR green norite	63.630	89.056	1.627	23
21 SR brown norite	63.674	88.743	1.719	40
19 SR amphibolite	63.534	90.373	1.111	1
18168-1 NR oxide-rich gab.	63.475	90.227	1.171	4
18173-4 NR felsic norite	63.427	89.112	1.544	18
13741-4 NR mafic norite	63.564	88.274	1.913	30
C672572 NR mafic norite	63.488	90.288	1.168	3
C672572-2 NR felsic incl.	63.460	90.318	1.153	1
27 NR mafic footwall	63.683	88.482	1.789	45
28 NR mafic footwall	63.508	88.615	1.697	25
30 NR mafic footwall	63.561	88.729	1.697	28

B. K-feldspar	Or(V)	Or(b^*c^*)	$\Delta(bc)$	$(\alpha^*\gamma^*)$	$t_1 0$
44-73A NR BT lava	106.5	101.9	0.81	0	0.40
44-73B NR BT	96.8	103.4	0.90	0	0.45
13094-1 SR BT lava	96.2	103.0	0.91	0	0.45
16156-4 NR BT lava	103.4	100.3	0.82	0	0.41
31-73 NR BT	91.9	97.3	0.90	0	0.45
10933-10 SR granophyre	96.7	102.0	0.97	0.92	0.94
10171-19 SR granophyre	95.1	100.3	0.99	1.00	0.99
14697-4 SR granophyre	97.4	98.9	1.01	0.99	1.00
13 SR aplite inclusion	95.7	97.8	1.02	0.97	1.00
2C NR felsic inclusion	94.3	95.5	0.96	0.75	0.85
2B NR granophyre	99.4	102.4	0.93	0.85	0.89
2A NR granophyre	90.5	98.5	1.16	0.38	0.77
47-72 NR granophyre	102.7	103.0	0.91	0	0.45
48-72 NR granophyre	94.4	98.4	0.77	0	0.38
81-128 NR matrix	96.4	97.0	0.97	0.90	0.94
49-72 NR granophyre	97.9	98.5	0.90	0.80	0.85

The raw data on which these indicators are based are reported in Tables 2 (norite), 3 (granophyre) and 5 (Onaping tuffs). Definitions: $\Delta 131 \equiv 2\theta(131) - 2\theta(1\bar{3}1)$, Cu$K\alpha_1$ radiation; Or(V) is Or content based on unit-cell volume (Stewart & Wright 1974); Or(b^*c^*) is Or content based on co-ordinates in the b^* - c^* diagram (Blasi 1977); $\Delta(bc) \equiv t_1 0 + t_1 m$; $\Delta(\alpha^*\gamma^*) \equiv t_1 0 - t_1 m$ [calculated according to the expressions of Blasi (1977)], whence $t_1 0$, the proportion of Al statistically occupying the $T_1 0$ position. Units: β^*, γ^* and $\Delta 131$ in degrees, An, Or(V) and Or(b^*c^*) in mol.%. The location and petrographic description of the samples are provided in Table 1. Abbreviations: NR North Range, SR South Range, BT black tuff, GT grey tuff, rhy rhyolite, incl. inclusion, gab. gabbro, qte quartzite. An content of plagioclase is estimated from the β^* - γ^* plot. Average standard error associated with β^*: 0.025° (black tuff), 0.018° (grey tuff), 0.020° (granophyre), 0.021° (norite); with γ^*: 0.034° (black tuff), 0.018° (grey tuff), 0.025° (granophyre), 0.032° (norite); with $\Delta(bc)$ and $\Delta(\alpha^*\gamma^*)$: 0.02 (1σ). The samples are listed here in stratigraphic order, as in Table 1 and Figures 1 and 6.

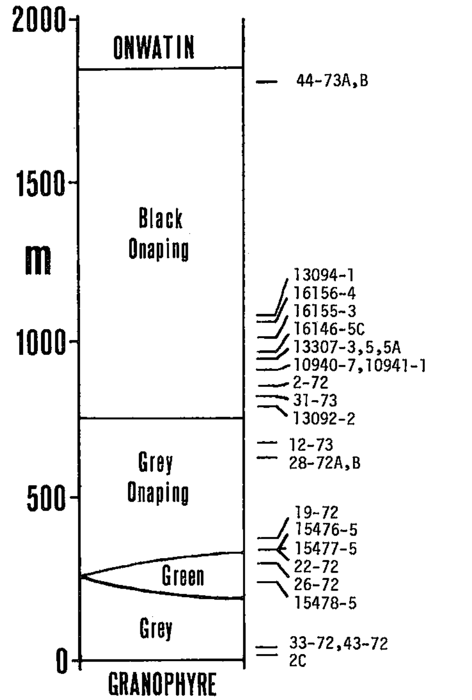

FIG. 5. Stratigraphic column for the Onaping Formation, showing the map-units recognized, their thickness, and locations of specimens selected for study.

turally intermediate microcline. The microcline in the granophyre from the South Range is better ordered than that from the North Range. In two samples of grey granophyre from the North Range, the conversion of orthoclase to microcline has not occurred. The composition of the K-feldspar, inferred from the b^* and c^* values and from unit-cell volume V, ranges from 94 to 100% Or (Table 4). This range is indicative of compositional re-equilibration of the K-feldspar at a temperature below 300°C.

Discussion

Microcline and sodic plagioclase in granophyre generally have re-equilibrated compositionally, but some have failed to re-equilibrate structurally. In the North Range, granophyre locally may still preserve orthoclase. The scale of the grid pattern defined by albite- and pericline-twinned domains is expected to be submicroscopic in structurally intermediate microcline. As much of the granophyre contains a K-feldspar with visible grid-twinning, we consider low microcline to be characteristic of most of the unit. The two orthoclase-bearing samples do not contain an anomalously calcic or disordered plagioclase. This may indicate that in this part of the North Range, changes in the plagioclase occurred above the field of stability of microcline, *i.e.,* above 400°C, and that below this temperature, the conversion to microcline was somehow impeded by abrupt cooling, caused perhaps by rapid uplift and denudation.

Useful geothermometric information cannot be extracted from the data presented on K-feldspar – plagioclase assemblages, nor can an inference be made concerning the nature of the original assemblage of feldspars. Sanidine has not survived. Some primary plagioclase may occur in North-Range granophyre that contains orthoclase or intermediate microcline.

Feldspar Mineralogy of the Onaping Tuffs

Petrographic details

The grey Onaping tuff has been so extensively recrystallized that in polarized light the pyroclastic textures readily seen in the overlying black tuff (see below) are scarcely recognizeable. However, in plane light, these textures are readily seen. A distinctive rim around most of the pumice fragments has been likened (Stevenson 1972) to the pectinate rim of quartz + albite that surrounds fragments of pumice in ash-flow tuff (Smith 1960, Ross & Smith 1961).

In the black Onaping tuff, lapilli and pectinate rim are well preserved and more conspicuous than in the grey tuff. Devitrified pumice fragments generally range in size between 3 and 5 mm, but some are much larger; few are flattened. Relatively coarse quartz and albite crystals fill vesicles in the unflattened pumice fragments, as in young ash-flow tuffs subjected to vapor-phase crystallization (Ross & Smith 1961).

Plagioclase

Data are reported for the pumice fragments, their pectinate rims, for various xenoliths and for the aphanitic matrix of the tuffs. Figure 5 shows the stratigraphic position of the samples, and Table 5 contains the results of the cell-parameter refinements (available from the Depository of Unpublished Data, CISTI, National Research Council, Ottawa, Ontario K1A 0S2).

Samples of the Onaping tuff contain nearly pure albite (star, Figs. 6A, B). The data points define an elongate array perpendicular to the locus of ordered structures; the array intersects this line in the interval An_1 to An_3. The points below a β^* value of 63.490° are attributed a slight Al-Si disorder; there is no explanation at present for plagioclase that is apparently better ordered than fully ordered albite (*i.e.,* values of β^* greater than 63.490° for a γ^* of approximately 90.4°). The departure in the most

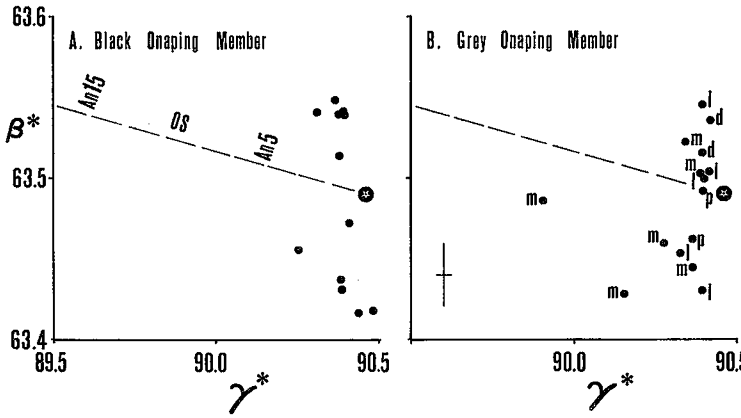

FIG. 6. Plot of β^* *versus* γ^* in plagioclase in the Onaping tuff. The dashed line OS marks the locus of ordered structures; end-member ordered albite: encircled star. The approximate location of An_{15} and An_5 is indicated. An average error-bar is also plotted. A. Black Onaping tuff. All the samples plotted represent plagioclase in the devitrified matrix. B. Grey Onaping tuff (includes samples of green tuff). Symbols: p pectinate rim, d clast of devitrified pumice, 1 lithic clast, m matrix of tuff. Points below the dashed line OS indicate slight Al–Si disorder. Points above the dashed line cannot be explained at present (see text).

aberrant samples is within twice the standard error in β^*. Such albite is found in clasts of devitrified pumice and footwall rocks in the grey Onaping, and in the aphanitic matrix in both grey and black Onaping (Figs. 6A, B). The plagioclase in these subsamples is of replacement or transformation origin. Note, however, that as many data-points for plagioclase of such an origin plot below the locus of ordered structures as plot above it. Different subsamples of a single specimen may have different values of β^*. Albite having a β^* exceeding 63.54° has not been found in the few other suites examined using the same technique.

No dependence of the degree of order with depth in the 1.8-km-thick unit was found, nor are there differences between North- and South-Range specimens. Compared to the analogous diagram for samples of norite (Fig. 2) and granophyre (Fig. 3), the tuffs contain a sodic plagioclase that is closer to the ordered, pure albite expected if equilibrium is attained in the system Ab-An below 400°C. This is attributed to 1) the fine grain-size of the tuff, which insures efficient interaction with a pore fluid, and 2) for samples of pectinate rims and pumice with infilled vesicles, the volumetric importance of albite deposited directly from a fluid phase and not originating as a product of devitrification or replacement.

Two samples of the black tuff member are devoid of albite; 100% of the feldspar is K-feldspar: 1) 44–73A, a lens of milky lava found near the top of the black tuff unit, and 2) 16156–4, a lens of spherulitic lava from 250 m above the base of the black tuff member.

K-feldspar

K-feldspar was found in only two of the fifteen samples of the grey tuff member. One, 22–72, from a long lens of densely welded rhyolitic tuff near the base of the grey tuff, contains intermediate microcline (t_1O 0.63) volumetrically subordinate to the albite; the other, 2C, a fragment of recrystallized footwall rock, contains nearly equal quantities of intermediate microcline (t_1O 0.85) and albite. The microcline in both cases is relatively pure (N_{Or} 0.96 and 0.94, respectively), which indicates equilibration at a low temperature. Structurally, the microcline has failed to convert to low microcline, presumably because of abrupt cooling and mildness of the metamorphic overprints.

K-feldspar is relatively more prevalent in the black Onaping tuff; 8 of the 12 samples contain K-feldspar + albite. In all, the K-feldspar is orthoclase (Fig. 7). The four K-feldspar-free samples are from the lower fifth of the unit. As in the grey tuff, the orthoclase in the black tuff contains approximately 96% Or (Table 4), which indicates compositional equilibration with coexisting albite (where available) and a fluid phase at a temperature less than 300°C.

Discussion

Tuffs of the Onaping Formation are mineralogically and chemically zoned. Much of the grey tuff member is devoid of K-feldspar, whereas the reverse is true of the upper half of the black tuff member. As many of the specimens that define this vertical zonation consist of devitrified glass, it is tempting to attribute this pattern to a redistribution of the alkalis upon devitrification.

The efficient separation of Na and K cannot be considered to be due to crystal fractionation in a magma chamber; Hildreth (1979) showed that there might be complementary gradients in Na and K in a magma reservoir that would be reflected in inverse fashion in the ignimbritic products of an eruption. However, Hildreth's gradients are subtle, and nowhere lead to K-feldspar- or albite-free rocks. We contend, as did Scott (1966) and White & Martin (1980), that it was during the cooling of the pile of pyroclastic material that the major episode of alkali mobilization occurred. In relative terms, the solubility of K-feldspar is greater at high temperature, whereas that of albite is greater at low temperature (Orville 1963). Given the upwardly decreasing tem-

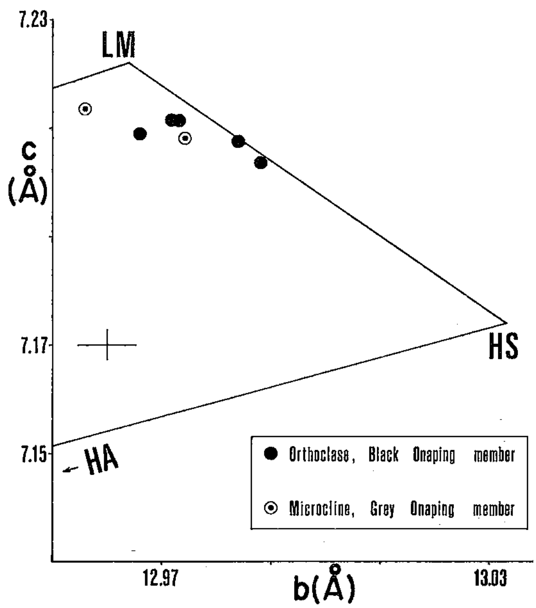

FIG. 7. Plot of the cell edges *b versus c* for K-feldspar in tuffs of the Onaping Formation. Symbols: LM low microcline, HS high sanidine, HA high albite. An average error-bar is plotted. The relatively large errors probably reflect the lack of structural and compositional homogeneity of K-feldspar in the tuffs.

peratures in a thick pile of tuff in which H_2O is progressively liberated as the pumice fragments flatten and as glass containing some dissolved water devitrifies, sodium can be expected to concentrate by ion exchange near the relatively hotter base, and potassium near the relatively cooler top of the pile. A large interval near the middle will contain subequal concentrations of Na and K, but their ratio is likely to have been disturbed during cooling. Ion-exchange reactions of the type studied by Orville (1963) achieve equilibrium very quickly.

The black Onaping tuff contains carbonaceous material, shows signs of reworking in a sedimentary basin, and grades into the overlying Onwatin slate. One might propose that the upward enrichment in K reflects an increasingly important K-feldspar-bearing detrital component, shed by the surrounding basement rocks. The type of K-feldspar in the country rocks is microcline (Gibbins & McNutt 1975), not orthoclase. In addition, it is unlikely that K-feldspar would be shed in the sedimentary basin to the exclusion of sodic plagioclase, also a major constituent of the country rocks. The K-feldspar in the tuff thus does not appear to be detrital in origin.

The presence of monoclinic K-feldspar in the black Onaping is anomalous and indicates that conversion to microcline below 400°C failed to occur, possibly for kinetic reasons. The rate of cooling at the top of the Onaping was simply too rapid through the interval 400 - 200°C for this sluggish reaction to occur. Compositional equilibrium, involving Na-for-K exchange, was maintained as cooling occurred. Below 200°C, experimental studies show that the rate of Al-Si ordering approaches zero. The persistence of orthoclase in the black tuff also indicates that any metamorphic overprint was not sufficiently intense to promote the conversion of orthoclase to low microcline. All but one of the localities of orthoclase are on the northern flank of the Basin, where the intensity of the metamorphic overprint is known to have been weaker than on the South Range.

The proposal that the Onaping Formation is vertically zoned is not new; it was first proposed by Stevenson (1972) and documented more fully by Muir & Peredery (1984). The base is not only more sodic but also is more felsic than the top of the sequence. Some of our samples of black Onaping tuff are more K-enriched than those documented by Muir & Peredery (1984). We contend that the zonation in Na and K is not a primary feature, but one that reflects metasomatic redistribution throughout the pyroclastic blanket. Whether the phenomenon is sufficiently regular that bulk K/Na values could be contoured remains to be tested. The hypothesis implies that the Onaping tuff presently contains no minerals with pristine compositions.

The subtle metasomatic changes here proposed shed light on the mode of formation of a pectinate rim, a texture characteristic of ash-flow tuffs that has never been properly explained. Albitization of K-feldspar near the base of the Onaping would cause an 8% shrinkage owing to the relatively smaller unit-cell volume of albite. A shrinkage of comparable magnitude occurred concomitant with devitrification. Owing to this volume reduction, which occurred after the flattening of the pumice fragments, an open space developed around each fragment undergoing shrinkage, as it pulled back from the fine-grained matrix of devitrified shards and pulverized lithic and crystal fragments. Owing to their large relative surface-area, the small shards would have devitrified before the larger pumice fragments. The pectinate rim thus develops as a product of vapor-phase crystallization around each fragment of pumice. Albite and quartz deposited here, as an infilling of vesicles and as a cement in the porous matrix, will skew the bulk composition of the Na-enriched portions of the Onaping even further from the magma's composition than would be expected by simple exchange of Na for K in the feldspar structure.

A combination of ion-exchange and infiltration metasomatism processes, with their attendant changes in volume, is held responsible for the extensive recrystallization and modification of the original pyroclastic textures in the grey tuff. This textural disturbance in the Onaping Formation is but one of the many enigmatic features that confront the investigator of these controversial rocks (Stevenson 1984a).

General Discussion

In theory, at least, many of the uncertainties concerning the formation of the norite, granophyre and Onaping tuffs could be removed if the feldspar mineralogy of these rocks could be understood. Our survey is of necessity cursory, but the data establish an interesting pattern of vertical zonation in the degree of Al–Si order of K-feldspar. Well-ordered microcline is an accessory in the norite. In the granophyre, low microcline is widespread, but intermediate microcline and orthoclase also occur. Only relatively disordered K-feldspar occurs near the top of the black Onaping member. This suggests that all the rocks cooled as a single unit.

The rocks no longer contain original magmatic assemblages of feldspars. The data of Taylor (1968) and Ding & Schwarcz (1984) on oxygen isotope geochemistry are consistent with this observation. Pristine norite contains labradorite that has changed from disordered to completely ordered. Although such transitions may be diffusion-related and thus may not involve water, we consider this unlikely. The probability of finding primary feldspar compositions drops markedly as the upper gabbro is approached. The changes are thorough in rocks containing a granophyric intergrowth as, upon cooling, differential contraction of the component minerals causes such rocks to become porous and permeable, and thus prone to isotopic re-equilibration (Taylor 1968). The results of Ding & Schwarcz (1984) are consistent with the proposal that the disturbance is most thorough in the Onaping Formation, probably a reflection of porosity and permeability enhanced by devitrification and thermal contraction.

Along with Na, K and Ca, other elements hosted by the feldspars (*e.g.*, Rb, Sr, Ba, a portion of the rare earths) may also have been mobilized. On the basis of rare-earth distributions, norite and granophyre are considered genetically linked (Kuo & Crocket 1979). The Onaping tuffs were considered unrelated because they typically contain only half the rare-earth-element content of the granophyre, and because the indicators of magmatic evolution have more primitive values than in the granophyre. But the possibility exists that the rare earths were partly mobilized with Na and K. In future programs of geochemical sampling, the feldspar assemblage could be used as a sensitive screen to evaluate which specimens are least likely to have been intensely disturbed.

The rocks of the South Range are equilibrated to a slightly greater degree than those of the North Range, owing presumably to a stronger metamorphic overprint. North-Range rocks are at a subgreenschist metamorphic grade, whereas South-Range assemblages indicate a low to middle greenschist grade (Card 1978, p. 275). This difference is not a major factor in explaining the observed feldspar mineralogy of the Sudbury rocks; the mineral assemblage in South-Range rocks shows signs of metastable preservation of the high-temperature feldspars also. The episodes of regional metamorphism recorded in this area, if sufficiently intense to lead to greenschist-grade assemblages, would be expected to have eliminated the metastable feldspars documented here. The persistence of partly converted high-temperature feldspars suggests that the metamorphic events were very mild, a principal conclusion of Masliwec & York (1984) on the basis of $^{40}Ar/^{39}Ar$ dating. Their data indicate that the Grenville event was the most prominent to affect this area.

Extensive conversion of the assemblage of magmatic feldspars to a subsolidus assemblage took place as the complex cooled. The extensive development of the new assemblages requires that a major role be attributed to an interstitial, mobile aqueous fluid. The pervasiveness of the transformations in the upper part of the stratiform complex and in rocks of the Onaping Formation suggests to us that the water was largely of magmatic derivation and not due to infiltration from outside the complex.

The question of the origin of the Onaping tuffs, whether endogenic, the product of explosive volcanism, or exogenic, consisting of fall-back material following a meteoritic impact, still is the subject of controversy (Muir & Peredery 1984, Peredery & Morrison 1984, Stevenson 1984b). As an argument in favor of an endogenic origin, there is no *a priori* reason why a huge body of impact-generated melt should be anywhere close to water saturation. The zonation in Na and K in the Onaping tuffs developed as the thick section cooled, and required ion-exchange reactions involving a hot aqueous fluid. The emplacement of ignimbritic material, by definition saturated with H_2O upon emplacement (Sparks *et al.* 1973), satisfies our requirements concerning the widespread availability of water in isotopic equilibrium with the rocks as they cooled. To propose that the observed changes in bulk composition and feldspar mineralogy occurred during the cooling of an initially dry impact-generated melt would raise serious conceptual difficulties concerning the source of the water and the mechanism to introduce it throughout the 1.8-km-thick pile in a short interval of time. The top of the black Onaping is intercalated with water-laid volcanogenic sediments, but the infiltration of the overlying column of water cannot be responsible for the thorough and pervasive subsolidus changes.

If the coeval norite, granophyre and Onaping tuffs are genetically linked products of fractional crystallization of basic parental magma, the size of the subjacent magma-reservoir must have been unusually large. In fact, geophysical modeling indicates the presence of high-density basic and ultrabasic rocks beneath the Sudbury structure, at a depth of 2 to 6 km and over a significantly broader area than the structure itself (Card *et al.* 1984, Gupta *et al.* 1984). The evisceration of the H_2O-saturated apical parts of such a vast reservoir of differentiating magma could have led to events of unusual violence. These events may account for the development of the shock-related material present in the area.

Acknowledgements

Most of the data reported in this paper are taken from a M.Sc. thesis written by Eva S. Schandl and submitted to the Department of Geological Sciences, McGill University. We acknowledge the help of Mr. Richard Yates and Ms. Vicki LoSchiavo, and the continuing support of the Natural Sciences and Engineering Research Council (operating grant A7721 to R.F. Martin). We acknowledge the very useful comments of the reviewers, K.D. Card and P.B. Robertson. Associate Editor Tomás Feininger helped us greatly to express our findings concisely.

References

Appleman, D.E. & Evans, H.T., Jr. (1973): Job 9214: indexing and least squares refinement of powder diffraction data. *U.S. Geol. Surv. Comp. Contr.* **20.**

BLASI, A. (1977): Calculation of T-site occupancies in alkali feldspar from refined lattice constants. *Mineral. Mag.* **41**, 525-526.

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.

CARD, K.D. (1978): Metamorphism of the 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.

______, 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.

DAVIS, T.E. & SLEMMONS, D.B. (1962): Observations on order-disorder relations of natural plagioclase. III. Highly ordered plagioclases from the Sudbury intrusive, Ontario, Canada. *Norsk Geol. Tidsskr.* **42(2)**, 567-577.

DING, T.P. & SCHWARCZ, H.P. (1984): Oxygen isotopic and chemical compositions of rocks of the Sudbury Basin, Ontario. *Can. J. Earth Sci.* **21**, 305-318.

GIBBINS, W.A. & MCNUTT, R.H. (1975): The age of the Sudbury Nickel Irruptive and the Murray granite. *Can. J. Earth Sci.* **12**, 1970-1989.

GUPTA, V.K., GRANT, F.S. & CARD, K.D. (1984): Gravity and magnetic characteristics 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**, 381-410.

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

HILDRETH, W. (1979): The Bishop tuff: evidence for the origin of compositional zonation in silicic magma chambers. *Geol. Soc. Amer. Spec. Pap.* **180**, 43-75.

KROGH, T.E., DAVIS, D.W. & CORFU, F. (1984): Precise U-Pb zircon and baddeleyite ages for 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**, 431-446.

______, MCNUTT, R.H. & DAVIS, G.L. (1982): Two high precision U-Pb zircon ages for the Sudbury Nickel Irruptive. *Can. J. Earth Sci.* **19**, 723-728.

KROLL, H. & RIBBE, P.H. (1983): Lattice parameters, composition and Al,Si order in alkali feldspars. *In* Feldspar Mineralogy (second edition, P.H. Ribbe, ed.). *Mineral. Soc. Amer., Rev. Mineral.* **2**, 57-99.

KUO, H.Y. & CROCKET, J.H. (1979): Rare earth elements in the Sudbury Nickel Irruptive: comparison with layered gabbros and implications for Nickel Irruptive petrogenesis. *Econ. Geol.* **74**, 590-605.

MARTIN, R.F. (1984): Trends of albitization in the Montgenèvre ophiolite, Western Alps. *Bull. Minéral.* **107**, 345-356.

MASLIWEC, A. & YORK, D. (1984): $^{40}Ar/^{39}Ar$ dating of Sudbury minerals. *Geol. Assoc. Can. – Mineral. Assoc. Can. Program Abstr.* **9**, 88.

MOODY, J.B., JENKINS, J.E. & MEYER, D. (1985): An experimental investigation of the albitization of plagioclase. *Can. Mineral.* **23**, 583-596.

MUIR, T.L. & PEREDERY, W.V. (1984): The Onaping Formation. *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**, 139-210.

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.

ORVILLE, P.M. (1963): Alkali ion exchange between vapor and feldspar phases. *Amer. J. Sci.* **261**, 201-237.

PEREDERY, W.V. (1972): Chemistry of fluidal glasses and melt bodies in the Onaping Formation. *Geol. Assoc. Can. Spec. Pap.* **10**, 49-59.

______ & MORRISON, G.G. (1984): Discussion of the origin 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**, 491-511.

______ & NALDRETT, A.J. (1975): Petrology of the Upper Irruptive rocks, Sudbury, Ontario. *Econ. Geol.* **70**, 164-175.

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

ROSS, C.S. & SMITH, R.L. (1961): Ash-flow tuffs – their origin, geologic relations and identification. *U.S. Geol. Surv. Prof. Pap.* **366**.

SCOTT, R. (1966): Origin of chemical variations within ignimbritic cooling units. *Amer. J. Sci.* **264**, 273-288.

SCRIBBINS, B.T., RAE, D.R. & NALDRETT, A.J. (1984): Mafic and ultramafic inclusions in the sublayer of the Sudbury igneous complex. *Can. Mineral.* **22**, 67-75.

SMITH, J.V. (1975): *Feldspar Minerals.* **1.** *Crystal Structure and Physical Properties.* Springer-Verlag, New York.

SMITH, R.L. (1960): Ash-flows. *Geol. Soc. Amer. Bull.* **71**, 795-841.

SPARKS, R.S.J., SELF, S. & WALKER, G.P.L. (1973): Products of ignimbrite eruptions. *Geology* **1**, 115-118.

STEVENSON, J.S. (1972): The Onaping ash-flow sheet, Sudbury, Ontario. *Geol. Assoc. Can. Spec. Pap.* **10**, 41-48.

______ (1984a): Sudbury problems and suggestions for further research. *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**, 523-531.

______ (1984b): Welded rhyolitic tuff (ignimbrite) from the Onaping Formation, Sudbury, Ontario. *Geol. Assoc. Can. — Mineral. Assoc. Can. Program Abstr.* **9**, 108.

______ & COLGROVE, G.L. (1968): The Sudbury Irruptive: some petrogenetic concepts based on recent field work. *Int. Geol. Congress 23rd, Sect.* **4**, **5**, 27-35.

STEWART, D.B. & WRIGHT, T.L. (1974): Al/Si order and symmetry of natural alkali feldspars and the relationship of strained cell parameters to bulk composition. *Bull. Soc. franç. Minéral. Crist.* **97**, 356-377.

TAYLOR, H.P., JR. (1968): The oxygen isotope geochemistry of igneous rocks. *Contr. Mineral. Petrology* **19**, 1-71.

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.

WHITE, M.V.W. & MARTIN, R.F. (1980): The metasomatic changes that accompany uranium mineralization in the nonorogenic rhyolites of the Upper Aillik Group, Labrador. *Can. Mineral.* **18**, 459-479.

Received May 16, 1986, revised manuscript accepted September 23, 1986.