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. Albition becomes pervasive near the top of the gabbro. The interstitial K-feldspar is well-ordered microcline. Granophyre contains albite (An₀₋₆₆), 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 (An₀₋₆₆), 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 reflétait un phénomène d’échange d’ions pendant le refroidissement de la nappe ignimbrite. L’albitisation 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.

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

<table>
<thead>
<tr>
<th>Tuff Type</th>
<th>Description</th>
<th>Location Details</th>
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<tr>
<td>Black tuff</td>
<td>Small frags, white</td>
<td>Centre E side L 10, C V, Capreol* NR</td>
</tr>
<tr>
<td></td>
<td>Silty bl t f mx</td>
<td>Same as for 44-73A</td>
</tr>
<tr>
<td>44-73A</td>
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<tr>
<td></td>
<td>Thin lens gy amyg</td>
<td>NW, L 1, C VI, Blezard SR</td>
</tr>
<tr>
<td>13094-1</td>
<td></td>
<td>Same as for 13094-1</td>
</tr>
<tr>
<td></td>
<td>Long lens gy spher.</td>
<td>SE, L 2, C 1, Wilsner NR</td>
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<tr>
<td>16156-4</td>
<td></td>
<td>Same as for 16156-4</td>
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<td></td>
<td>Bl t f</td>
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<tr>
<td>16155-3</td>
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<tr>
<td></td>
<td>Frag flinty gn &quot;rhy&quot; (welded rhy t f) in bl t f</td>
<td>SW, L 8, C IV, Dowling NR</td>
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<tr>
<td>16146-5C</td>
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<td>Same as for 16146-5C</td>
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<tr>
<td></td>
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<td></td>
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<tr>
<td>Grey tuff</td>
<td></td>
<td></td>
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<tr>
<td>12-73</td>
<td>Gy t f</td>
<td>Centre E side L 8, C VI, Capreol NR</td>
</tr>
<tr>
<td>28-72A</td>
<td>Qte pebble in t f c.p.</td>
<td>NW, L 10, C II, Norman NR</td>
</tr>
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<td>28-72B</td>
<td>Gy t f mx for 28-72A</td>
<td>Same as for 28-72B</td>
</tr>
<tr>
<td>19-72</td>
<td>Lens banded flinty gn &quot;rhy&quot; in gy t f</td>
<td>Centre L 10, C II, Norman NR</td>
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<td>15477-5</td>
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<td>Same as for 19-72</td>
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<tr>
<td>22-72</td>
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<td></td>
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<td></td>
<td>Frag Creighton gran in lens gn t f in gy t f</td>
<td>Same as for 26-72</td>
</tr>
<tr>
<td>43-72</td>
<td>Qte block at base of gy t f</td>
<td>Same as for 43-72</td>
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<tr>
<td>2C incl.</td>
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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...
Granophyre, South Range

10949-1 foliated upper grey granophyre east L 3, C III, Creighton
24 grey granophyre centre, L 7, C IV, Belzard, 500 m S Onaping cont. 2E, L 10, C IV, Snider, 700 m N nor contact
10933-10 felsic salmon grey granophyre NE4, L 5, C VI, Denison 200 m N nor contact
10171-19 felsic salmon grey granophyre L 10, C II, Creighton, 15 m N nor contact centre, L 3, C I, Rayside, close to upper gabbro
14697-4 mafic salmon gneissic grey granophyre same as for 12
12 oval f.g. felsic inclusion patch of f.g. felsite same as for 12
13 patch of f.g. felsite same as for 12
14 patch of f.g. felsite same as for 12
15 patch of f.g. felsite same as for 12
16 patch of f.g. felsite same as for 12

Granophyre, North Range

28 uppermost grey granophyre centre, L 8, C IV, Dowling, recryst. An₆+qtz in matrix of An₇ laths and f.g. gphr; matrix of 55m NE Onaping contact
2A uppermost grey granophyre NE4, L 9, C IV, Dowling, 300 m NE Onaping contact same as for 28
6 grey granophyre NE4, L 7, C VI, Carepool, 650 m NE Onaping contact same as for 28, railway cut same as for 6
7 grey granophyre same as for 6
10 grey granophyre NE4, L 7, C VI, Carepool, 650 m NE Onaping contact same as for 47-72
47-72 grey granophyre same as for 47-72
48-72 grey granophyre same as for 47-72
81-128 felsic patch in salmon S 1 0, C V, Dowling, recryst. An₆+qtz in matrix of stouter An₇, all in f.g. gphr; matrix of mafic norite; same as for 12
49-72 grey granophyre NE4, L 6, C VI, Carepool, 500 m SW nor contact

Norite and upper gabbro, South Range

10171-24 upper gabbro centre, L 5, C VI, Denison, recryst. An₆+qtz in matrix of An₇ laths and f.g. gphr; matrix of 55m NE Onaping contact
22A upper gabbro centre, L 5, C III, Belzard, 400 m N nor-qtz contact same as for 22A
22B sheared aplite same as for 22A
23 upper gabbro same as for 22A
23Gr gneissic patch same as for 22A
20 black norite SE4, L 5, C III, Belzard, 1.3 km N nor-fqtz contact
17 green norite SW4, L 11, C VI, McMinn, Hwy 14A, 0.5 km N nor-fqtz contact
21 black-brown norite centre, L 4, C II, Belzard, Hwy 69, near basal contact
19 amphibolite in 20 same as for 21

Norite and oxide-rich gabbro, North Range

18168-1 oxide-rich gabbro S L 6, C II, Bowell, 50 m N mpeg contact
18173-4 felsic norite NE4, L 5, C II, Bowell, 125 m S nor-fqtz contact, base of Foy offset
13741-4 mafic norite L 2, C VI-VI, Carepool, E Capre L, near fqtz contact
C672572-1 felsic norite SW4, L 10, C I, Bowell, at very base of mafic norite, same as for C672572-1
C672572-2 felsic inclusion

Abbreviations: L lot, C concession, bl tf black tuff, gy tf grey tuff, nor norite, gp granophyre, fwt 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, sph. 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 the 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 granophyres are listed separately for the North and South Ranges.
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, CuKα1 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 mm³) sample.

**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 An₆₅ to An₉₀, 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 (An₅₂-An₆₅) through the interval of black norite to the upper gabbro (An₃₁-An₄₅). The plagioclase changes abruptly to An₁-An₃ 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 An₅₅ to An₆₅, 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* to An50, whereas the rim ranges from An13 to An41. 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 (An56 to An5), but the rim reaches An24, 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 accomplished 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-mm³ 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 28, 30, 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 An30 to An9 (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 albition.

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 albition 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.](image-url)
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 completely 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 $\beta^*$, 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 $t_O$, the proportion of Al in the $T_O$ position, ranges from 0.85 to 1 (Table 4). In well-ordered microcline, $t_O$ equals 1; values of less than 0.92 characterize struc-
### A. Plagioclase

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<td>90.347</td>
<td>1.027</td>
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### B. K-feldspar

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### 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 naturally intermediate microcline. The microcline in the granophyre from the South Range is better defined 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.

FIG. 5. Stratigraphic column for the Onaping Formation, showing the map-units recognized, their thickness, and locations of specimens selected for study.
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 recognizable. 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 An15 An10. 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

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**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 An15 and An5 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, l 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 $\beta^*$. 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 sub-samples 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 sub-samples of a single specimen may have different values of $\beta^*$. Albite having a $\beta^*$ 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) 161564, 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 ($t_1$O 0.63) volumetrically subordinate to the albite; the other, 2C, a fragment of recrystallized footwall rock, contains nearly equal quantities of intermediate microcline ($t_1$O 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.](image)
temperatures in a thick pile of tuff in which H₂O 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-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. Albition 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 & Schwarz (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 granophytic intergrowth as, upon cooling, differen-
tial 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 40Ar/39Ar 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 H2O 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 H2O-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.

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