OBSERVATIONS ON ORDER-DISORDER RELATIONS OF NATURAL PLAGIOCLASE

III. Highly Ordered Plagioclases from the Sudbury Intrusive, Ontario, Canada

By

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Introduction

This study investigates the major rock-types in four traverses across three main layers of the Sudbury lopolith in Ontario, Canada (Figure 1). Two traverses, one on either side of the lopolith, sample all three zones; the other two traverses, both on the south side of the intrusion, sample the lower and middle members.

The principal purpose of this study was to determine whether or not in a deep-seated lopolith there is a variation in composition or order-disorder of the plagioclases, either vertically or laterally. This Pre-Cambrian intrusion is nearly 7,000 feet thick and intrudes a series of older granites and medium to high rank metamorphosed sediments and volcanic rocks. The three zones include the lower norite and quartz diorite zone, the middle hybrid zone, and the upper micropegmatite zone. The extensive development of such hydrous minerals as actinolite, sericite and chlorite suggest that crystallization of the upper parts was in a water-rich environment.

Petrography of the Sudbury Intrusive, Ontario, Canada

General Features

The area known as Sudbury basin is formed by an elliptically shaped lopolith approximately 37 miles long from northeast to southwest and 17 miles wide from northwest to southeast. It is of Keween-

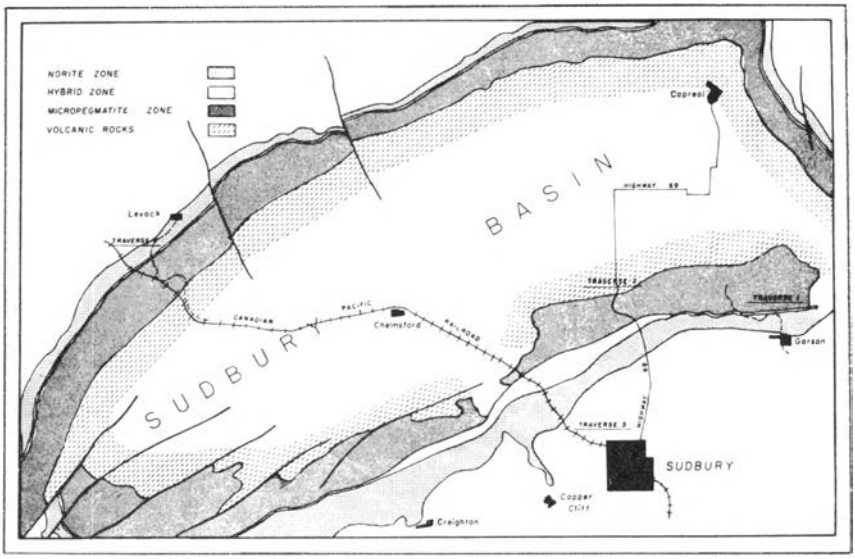

Figure 1. Index map showing the distribution of the main rock-types of the Sudbury lopolith, and the location of the traverses.

awan age. The thickness of the intrusion, calculated from an average dip of thirty-eight degrees, is nearly $1^1/_4$ miles.

The lower or outer part of the intrusive is usually referred to as norite. However, other terms such as quartz gabbro, diorite or quartz diorite have been used. The middle part is commonly referred to as the "hybrid zone" but has also been called the intermediate or transitional zone. The inner or upper part is termed the "granophyre" or micropegmatite.

Suggestions as to mode of emplacement of the lopolith have been advanced by several investigators. Walker (1897) hypothesized that the present relative position of the norite and micropegmatite was due to gravitative differentiation of homogenous magma which intruded as a flat sill and was folded after solidification into its present shape. Phemister (1925) thought that the two portions of the intrusive may have been emplaced at different times with the same reservoir as a source of magma, but with differentiation forming related but mineralogically distinct intrusions; the second intrusion was injected before complete solidification of the first. Knight (1917) felt that the

intrusive is in the form of a ring-like mass injected around a down faulted block now preserved within the igneous outcrop, and Yates (1938) says "a large syncline, existing previously, controlled the position and shape of the norite". The present petrographic examination of the rocks from the Basin suggests that some of the apparent difference may be caused from the degree of deuteric alteration rather than differentiation. The initial crystallization was at the outer (lower) margin with the gases and residual melt collecting near the upper part. Evidence for this is expressed in a gradual intensification of alteration from outer to inner margins of the intrusive.

These zones do not correspond exactly with any ordinary rock types. They are too basic for typical granite, with the mafic minerals approximating a diorite, while the high content of alkali feldspar and quartz exclude it from being classified a diorite. Although they closely approximates a granodiorite in composition, they texturally depart radically from that type.

Petrographic Types

The rocks of the Sudbury petrographic province are marked by a general mineralogical and textural uniformity. Most of the specimens of the suite of specimens are similar except for slight variation in abundance of accessory minerals, differences in composition of the plagioclase, and degree of alteration. The basal, relatively unaltered norite is a medium to coarse-grained, hypidiomorphic granular to locally sub-ophitic and diabasic, melanocratic rock consisting of augite, hornblende, hypersthene, biotite, plagioclase, titaniferous magnetite(?), interstitial quartz, alkali feldspar (usually in the form of microcline), and other accessories and alteration products which include sphene, apatite, epidote or zoisite, chlorite, sericite, calcite, and tremolite-actinolite.

Two distinct members are generally recognized in the norite zone in this province. The lower part of this member consists of plagioclase, amphibole, pyroxene, biotite and quartz. The plagioclase is markedly zoned with the inner portions of the crystals containing minute inclusions which give the mineral a brownish appearance in thin section. The plagioclase varies in composition from $Ab_{35}An_{65}$ to $Ab_{45}An_{55}$. The amphibole is of two types: 1) aggregates of short prisms pseudomorphous (?) after monoclinic pyroxene and 2) very green to

blue-green primary hornblende occurring as clots and separate crystals. Brown biotite is abundant and intimately associated with the blue-green amphibole. Quartz occurs as interstitial anhedral grains and appears to have replaced the plagioclase on its boundaries forming a pseudo-micrographic intergrowth.

Near the top of the norite zone, the most abundant mineral is dusty brown plagioclase. Orthopyroxene and hypersthene are common along with some interstitial quartz. Biotite is less abundant than in the lower portion of this member. There are slight changes in the mineralogy and texture of the rock: 1) quartz is more abundant, 2) orthorhombic pyroxene diminishes in abundance to leave only the monoclinic variety which may be sub-ophitic and 3) margins of the pyroxene are altered to green amphibole and their interiors may be uralitized to form needles of tremolite-actinolite.

In the normal micropegmatite of the province, the main constituent is a micropegmatitic intergrowth of quartz and feldspar but almost invariably there are scattered crystals of more sodic plagioclase approaching albite in composition. Epidote is the most common ferromagnesian mineral and occurs in clusters of fairly large crystals and separate grains in the dusty brown plagioclase. Associated also with the epidote is finely shredded biotite and blue-green amphibole. There is some apatite and calcite near the top of this zone.

Relative proportions of norite and micropegmatite vary in the North and South Ranges. The South Range apparently represents a deeper section of the intrusion than the North Range as it has probably been thrust up along faults crossing the center of the basin.

Paragenesis of Minerals

The parageneses of the minerals of the normal rock is clearly shown. Hypersthene and augite were generally the first minerals to crystallize, however, their crystallization overlaps in part with the next mineral to form, the plagioclase. Quartz, in granophyric intergrowth with sodic plagioclase, or rarely microcline, were the last important minerals to crystallize. They are anhedral and fill the interstices between the other minerals or corrode adjacent feldspars.

Alteration

Alteration of the plagioclase is nowhere as common or intense as

that in the pyroxenes, however even in the freshest looking norite there is incipient alteration of the centers of the larger plagioclase grains. When this alteration is intense, the large crystal looses its brown color and consists of zoisite or epidote and albite. When severe alteration of the plagioclase is visible, the brown color completely disappears to give a mixture of clear albite, epidote and amphibole.

General Mineralogy

Norite-Quartz Diorite Zone

The plagioclase is quite calcic in the norite-quartz diorite zone and tends to form prismatic crystals with a brownish tint though paler than in the typical material. Zoning is quite prominent and considerable replacement has occurred along crystal boundaries. Alteration is widespread with epidote and sericite as the products. Quartz and microperthite are abundant with the quartz occurring also as mosaics of grains. Blue-green to yellow-brown amphibole occurs poikilitically in fairly large crystals with the plagioclase and considerable quartz. Though some may be primary, epidote usually is an alteration product of plagioclase and as a component of the hornblende-biotite intergrowth. It also occurs as large secondary aggregates nearly the same size as the plagioclase crystals. Titanite is quite abundant and forms spherules with a grain of ilmenite at the center.

Hybrid Zone

The rock of the hybrid zone differs from the norite in the decidedly pink color and prismatic character of its feldspar as well as the lack of a diabasic texture. The plagioclase has become slightly to moderately more sodic being altered locally to sericite and epidote. The outer margins of the plagioclase consist of coarse microperthite which is continuous with the micrographic intergrowth of quartz and feldspar. There is an apparent increase in content of mafic minerals however there is considerable variation from place to place. The amphibole is the blue-green variety and it typically occurs as irregular intergrowths with biotite, quartz, titanite and ilmenite. It does not form pseudomorphs after any earlier crystallized mineral, but protrudes into the plagioclase and replaces it. Titanite is even more abundant and occurs in the same manner. Epidote and apatite are common also.

Table 1: Table of optical measurements, X-ray data, ordering indices, and anorthite percentage by specimen number.

Spec No.	Zone	Albite Twin Law		$2Vx$	(220)	$(1\bar{3}1)$	(131)	$(1\bar{3}1)$–(220)	(131)–$(1\bar{3}1)$	I.I.	An %
		X/TA	Y/TA								
92	Norite				28.43	29.60	31.48	1.17	1.88	54	55
97	–				28.53	29.79	31.59	1.26	1.70	166	59
122	–				28.34	29.72	31.42	1.28	1.70	188	65
121	–	69.0	65.5		28.42	29.73	31.51	1.31	1.78	155	62
120	–	73.0	67.0		28.44	29.77	31.51	1.33	1.79	145	59
119	–	72.5	66.5		28.30	29.66	31.45	1.36	1.79	140	57
118	–	72.5	67.5		28.39	29.72	31.45	1.33	1.73	155	57
117	Micro. Peg.	88.0	73.5		28.32	29.50	31.27	1.18	1.77	28	33
116	–	88.0	78.0		28.28	29.62	31.25	1.34	1.63	52	22
115	–	88.0	74.0		28.32	29.76	31.26	1.44	1.55	103	33
114	–	87.5	74.0		28.34	29.53	31.27	1.19	1.74	30	33
73	Hybrid	79.0	70.0		28.56	29.87	31.60	1.32	1.74	75	45
72	–	88.0	75.5		28.33	29.44	31.27	1.16	1.78	37	35
66	Norite			99.0	28.91	29.67	31.45	1.26	1.78	125	61
62	–			103.0	28.51	29.62	31.51	1.11	1.89	51	58
61	–				28.37	29.61	31.48	1.24	1.87	86	60
60	Micro. Peg.				28.21	29.54	31.25	1.33	1.71	44	15
59	–	89.0	74.0	95.0	28.20	29.55	31.26	1.35	1.71	38	13
57	–				28.30	29.54	31.33	1.29	1.79	28	15
56	Hybrid				28.37	29.85	31.50	1.48	1.65	57	13
54	–			102.0	28.30	29.48	31.50	1.18	2.02	8	0
52	Norite	74.0	61.5	100.0	28.47	29.60	31.48	1.12	1.88	65	60
104	Dike			90.0	28.46	29.43	31.42	1.09	1.60	25	59

Micropegmatite Zone

The rocks of the micropegmatite zone are characterized by an abundance of pink feldspar crystals between which run lenses and patches of biotite. The dark minerals are again variable but on a whole are less abundant than in the hybrid zone. The plagioclase $Ab_{67}An_{33}$ is somewhat more sodic but all the crystals are not of the same composition. They are much altered to epidote and sericite and pass abruptly into microperthite on their borders. The biotite is present mainly as small flaky crystals, sometimes forming aggregates which include a

great deal of titanite and epidote. Apatite prisms are somewhat less abundant than in the norite and hybrid zones.

Discussion

The optical and X-ray diffraction measurements are summarized in Table 1, and plotted in Figures 2–3. The results are generally consistent for any given zone, but there are a few anomalous specimens (specimens 62 and 92 have unusually low I.I.'s for the norite zone,

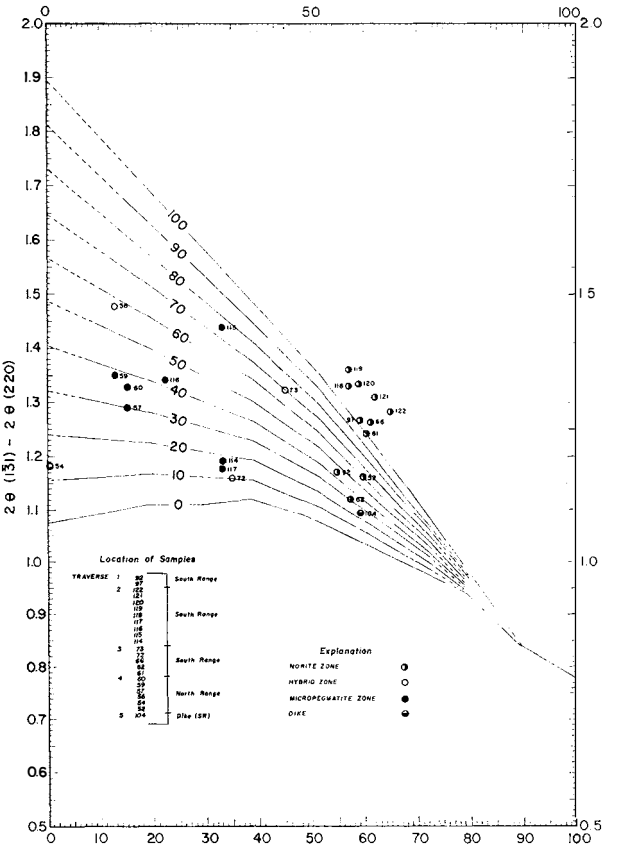

Figure 2. Order-disorder in natural plagioclase from the Sudbury lopolith as indicated by the 2θ angle between $2\theta\,(1\bar{3}1) - 2\theta\,(220)$ reflection and anorthite persentage. All data from X-ray diffraction patterns of ground rock specimens.

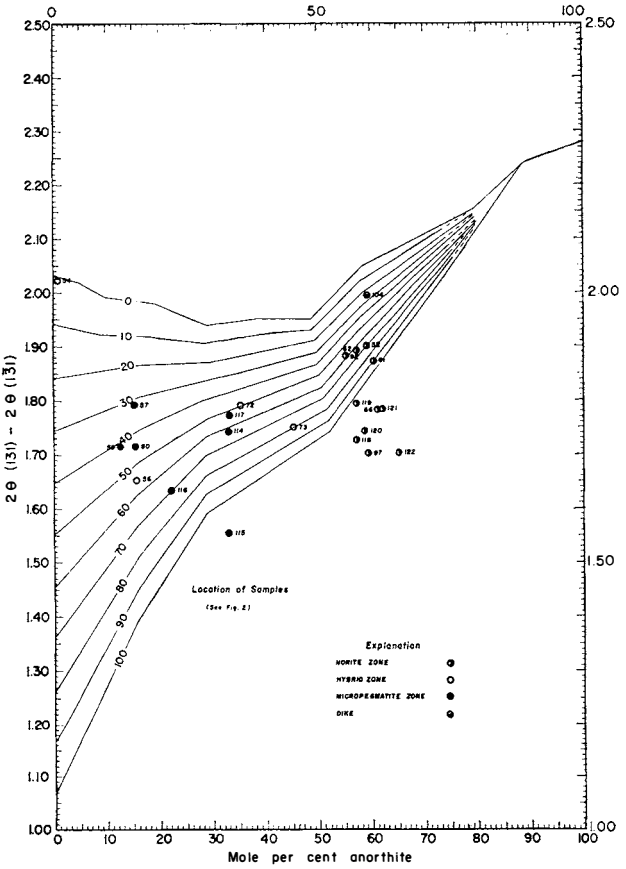

Figure 3. Order-disorder in natural plagioclase from the Sudbury lopolith as indicated by the 2θ angle between 2θ (131) − 2θ (1$\bar{3}$1) reflections and anorthite percentage.

and 115 has an unusually high I.I. for the micropegmatite zone). These erratic results could not be eliminated on the basis of errors in measurement and are therefore included in the data.

The norites have high intermediacy indices (103 to 188, by extrapolating the curves beyond 100) with a weak tendency for lower values upward in the norite and with decreasing anorthite percentage. The hybrid and micropegmatite types are normally distinctly lower (8 to 60) with no systematic variation in the vertical direction. The dike (specimen 104) has a very low intermediacy index (I.I. = 25).

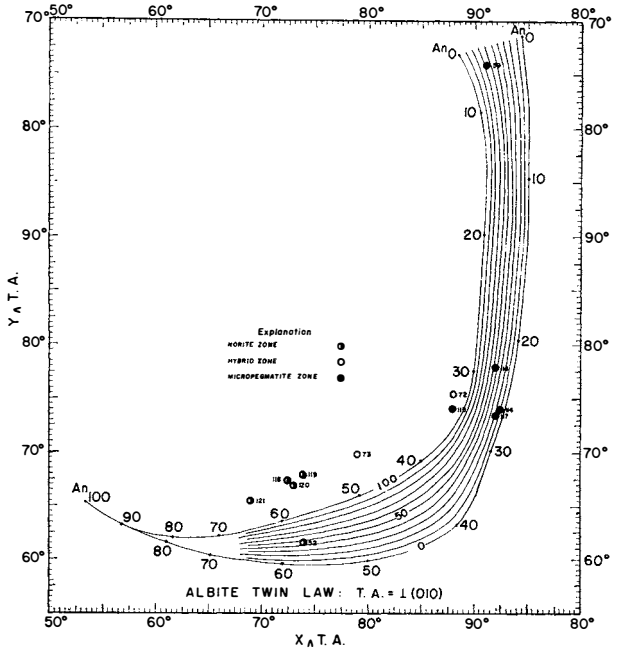

Figure 4. Order-disorder in natural plagioclace as determined by twin axis migration curves of the albite twin law. Highly ordered or plutonic types are represented by an I.I. of 100 and "high-temperature" or volcanic types by an I.I. of 0.

The intermediacy indices of the norite from the South range to the North Range do not show sufficient variation to support the hypothesis of Wilson (1956) that the South Range represents a deeper section of the lopolith. Ideally, deeper portions should show higher ordering having presumably cooled more slowly. However, insufficient specimens from the North Range norite zone may be responsible for the negative correlation.

When the range of ordering indices for each of the three zones are considered together, there does not appear to be any marked lateral variation in order-disorder relationships within the intrusion, at least to the extent where the method used is able to record order-disorder relations in plagioclases.

The sharp break in ordering indices at or near the boundary between the hybrid–norite zone tends to suggest a quite different cooling history or mechanism of ordering for the older norite. This is also

indicated by the sharp textural and mineralogical break at the same place. Above this discontinuity the plagioclase changes from brownish to pinkish in color and the anorthite persentage is more variable (the compositions are well below the An 55–65 range) of the normal norite and subophitic to diabasic textures are generally absent.

The abrupt changes in the type of palgioclase would seem to suggest a different ordering process and seemingly, therefore, a different cooling or hydrothermal history for the lower norite zone than for the upper hybrid and micropegmatite zones either due to multiple injection or by an abrupt change in the differentiation–crystallization mechanism.

Pure feldspar separations and additional study of the optical and X-ray character of the plagioclase appear to be warranted for the specimens in this unusual suite. Such studies may contribute data that not only may aid in resolution of some of the structural problems for this important area, but might also yield plagioclase in the An 55–65 range which are either structurally more thourougly ordered or have unusual chemistry.

The writers plan a more thorough study of the chemical and optical properties of these specimens and it is hoped that other workers will undertake more detailed plagioclase structural analysis.

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