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Crystallization history and textures of the Rearing Pond gabbro, northwestern Wisconsin

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Abstract

The Rearing Pond intrusion is a small basic body that displays a range of composition and textures illustrating its cooling history. Modal and mineralogical data indicate that it is a single differentiated unit or a cyclic unit in a larger poorly exposed intrusion.

Fractionation has resulted in a succession that varies from olivine cumulates through olivine–plagioclase–clinopyroxene cumulates to plagioclase clinopyroxene cumulates. Compositional variation of phases is small, with iron enrichment about 10 mole percent in the mafic phases and with plagioclase varying from An 80 to An 60. Some zoning of plagioclase is apparent, becoming stronger in the later units.

Primary clinopyroxene first appears as large oikocrysts in the olivine–plagioclase cumulates, and later changes to a granular habit in the olivine-free rocks. This is interpreted as a change in the ratio of growth to nucleation rates of the pyroxene corresponding to the cessation of olivine crystallization as the magma composition leaves the olivine field. This occurs at the quaternary invariant point, Fo–An–En–Di–Liquid in the system An,Di,Fo,SiO_2. The habit change occurs at this point as a result of the change in degree of supersaturation as the liquid fractionates past the invariant point as olivine is consumed. This is either a kinetic effect or a compositional one due to the differences in competition for components on opposite sides of the invariant point. Evidence suggests that both nucleation and growth accelerated in the latest rocks, as grain size is diminished and zoning becomes more pronounced.

Introduction

The textures of basic igneous rocks have received considerable attention through the years. Some notable examples have dealt with the ophitic texture (Krokström, 1932; Walker, 1957; Wager, 1961; Oppenheim, 1964). Others (Wager *et al.*, 1960; Hess, 1960; Wager, 1963) studied features of igneous sedimentation and the processes responsible for them, and Jackson (1967) developed a classification based on these processes. More recently a number of experimental studies based on classical theory of crystal nucleation and growth have provided new insight into the relationship between crystal habit, igneous textures and cooling history (Kirkpatrick, 1974; Lofgren, 1974; Swanson, 1977; Fenn, 1977).

It appears that textural relationships observed in these rock types are not only a function of rate of cooling but may also be controlled by the composition of the magma, which in turn is often the result of the degree of fractionation. The quaternary system anorthite–forsterite–diopside–silica (Osborn and Tait, 1952) illustrates the phase changes that occur with fractionation of a basaltic magma. In this paper the changes in cumulus minerals and related textural changes have been charted and compared with the magma composition, as determined by the petrographic analysis of the rocks, in an effort to explain the textural types and changes in type that have occurred. The example used is a small Keweenawan gabbro intrusion which displays a textural change from ophitic to granular that appears related to change in composition resulting from fractionation of a basaltic magma. Mineral compositions determined are approaching end-member compositions, so that the model provided by Osborn and Tait is an excellent starting point for development of an hypothesis relating texture to magma composition. It is unfortunate that a starting magma composition could not be determined for the intrusion.

Geologic setting

The Rearing Pond intrustion is one of several that lie along the southern boundary of the Keweenawan, Lake Superior syncline. The most common intrusive

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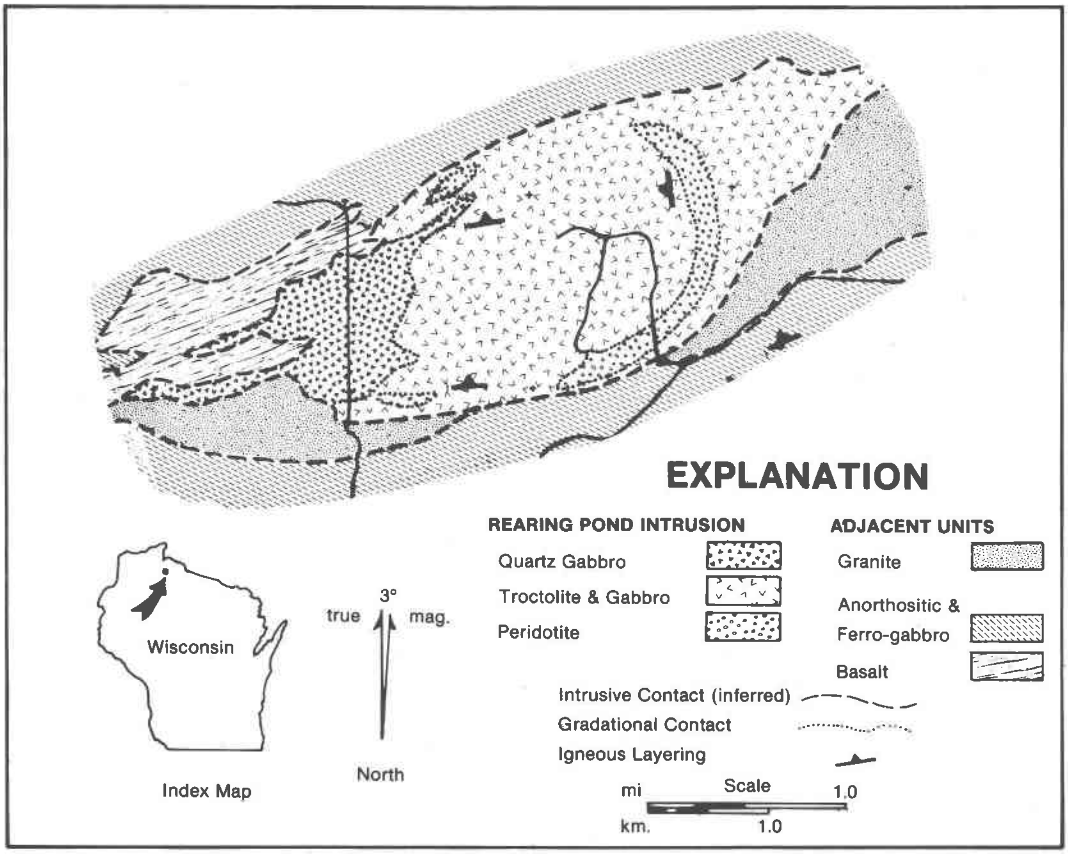

Fig. 1. Geological map of Rearing Pond intrusion. Rock units south of the intrusion are part of the Mineral Lake intrusion.

rocks are gabbro, anorthositic and troctolitic gabbro, and micrographic granites. Other related intrusive rocks, such as peridotite and occasional intermediate rocks, are found, but they are rare. The details of the structure and stratigraphy of the Keweenawan and older Precambrian units of the region have been described by Aldrich (1929) and Leighton (1954), and several more recent reviews have been of value in understanding both local and regional problems (Halls, 1966; White, 1966; Weiblen and Morey, 1975). These and other studies (Olmsted, 1968; Hubbard, 1968, 1975; Books *et al.,* 1966) suggest that the intrusive units are tabular bodies emplaced along surfaces such as faults or unconformities and are of Middle Keweenawan age. Along its south limb the Keweenawan units of the Lake Superior syncline dip northwesterly with moderate to steep angles, exposing the units in cross section. The entire volcanic section, including the intrusives in this area, is on the order of 8000 to 10000 m thick. In the Mellen area the intrusions have been emplaced into the Lower Keweenawan lavas and have nearly engulfed them. The major intrusion west of Mellen is a large anorthositic unit called the Mineral Lake intrusion (Olmsted, 1968), which is about 5000 m thick and 18 km long.

The Rearing Pond intrusion occupies a conspicuous embayment in the top of the Mineral Lake intrusion. Intrusive relationships between the two units are not clear, as the contact is poorly exposed. Both units, however, intrude the Lower Keweenawan volcanics, which in some cases have been so engulfed that they are now little more than thin screens between intrusives. Figure 1 shows the Rearing Pond intrusion as a lens-shaped body tapering to the east between other igneous units and to the west in the volcanics. The orientation of igneous laminations and layering within the intrusion is shown in Figure 2, and suggests that the form of the body is that of an elongate funnel tilted to the northwest.

Figure 2 shows that when the regional dip is removed the dips of the internal structures all converge to a point beneath the center of the intrusion. The distribution of rock types also seems to indicate a tilted funnel or cone-like structure. The lowermost unit is a feldspathic peridotite which forms a layer or envelope about the centrally-situated main mass of

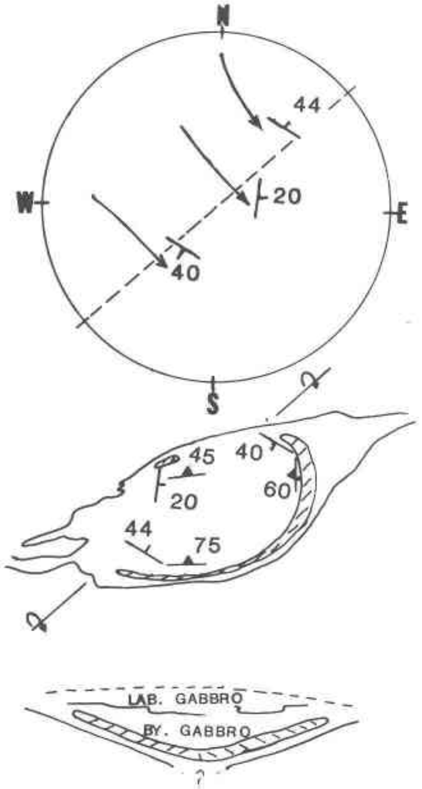

Fig. 2. Structural interpretation of igneous layering data and rock type distribution. Upper: Measured orientation of layering shown at tails of arrows. Removal of regional dip by rotation about horizontal axis, which is shown as dashed line, results in the orientations shown at heads of arrows. The 44° average dip located in the southwest corner of the intrusion, the 20° dip at the northwestern end, and the 40° dip in the east central area are shown in Fig. 1. The result is the new strikes all roughly parallel the perimeter of the body with dips toward the center, as shown in the center diagram. This 60° rotation of all values is justified by a 60° average regional dip of the Keweenawan sedimentary and volcanic units. The lower diagram is an interpreted north–south cross section, restored to the original orientation.

troctolitic rocks. The uppermost unit is a quartz gabbro which is clearly the product of fractionation of a more basic magma. In general, layering is not widespread, but in the higher parts of the intrusion some rhythmic layering, both graded and unimodal, has been observed. The implication of this lack of small-scale layering in the lower units is that convection was either very slow or not periodic until the later stage of the igneous cooling period.

Petrographic descriptions

The Rearing Pond intrusion has been divided into three units that are petrographically distinct and readily recognized in the field. Mineral compositions are shown in Table 1 and Figure 3. The earliest unit in a fractionation sequence is the peridotite (an olivine cumulate) that forms the envelope around the central unit. Next are the troctolitic rocks (olivine–plagioclase cumulate, with and without pyroxene oikocrysts), which form much of the central part of the intrusion and account for about eighty percent of its exposed area. The uppermost unit is quartz gabbro (plagioclase–clinopyroxene cumulate) found in the northwestern corner of the intrusion. Actual con-

Table 1. Modal analyses

PERIDOTITE

	W-74	W-204
Olivine*	72.4	59.7
Plagioclase	24.3	23.2
Biotite	-	0.7
Orthopyroxene	0.2	7.7
Clinopyroxene	2.2	4.7
Opaque	1.1	4.2
Number of counts	3500	3245

OLIVINE BEARING GABBRO AND TROCTOLITE

	Leuco-Troctolite W-125L	Mafic-Troctolite W-163	Spotted Gabbro W-39	Noritic W-46
Olivine*	23.4	39.7	13.8	3.1
Plagioclase	72.8	52.8	54.6	60.1
Biotite	-	-	-	0.2
Orthopyroxene	2.7	2.2	5.4	20.9
Clinopyroxene	0.5	5.1	25.6	9.4
Apatite	-	-	-	0.1
Secondary Chlorite or Hornblende	-	0.6	-	1.4
Magnetite	0.6	0.6	0.6	3.1
Number of counts	1400	1555	9800	1600

GABBRO (Rocks of Granular Texture)

	W-6	W-126	W-19	W-164	W-166
Plagioclase	55.6	48.7	61.7	52.7	55.0
Clinopyroxene	13.2	30.6	14.1	25.5	34.0
Orthopyroxene	15.7	3.9	12.9	7.6	8.9
Olivine*	0.5	15.8	2.1	-	-
Biotite	0.1	-	0.8	3.2	-
Magnetite	0.3	0.9	0.5	4.3	0.8
Apatite	Tr	Tr	Tr	0.4	Tr
Amphibole	14.6	-	7.9	1.0	1.2
Quartz	-	-	-	3.0	-
Alkali Feldspar	-	-	-	.4	-
Zircon	-	-	-	Tr	-
Number of counts	1400	1800	1548	1612	1400

*Serpentine was always counted as olivine. In some examples olivine was as much as 90% serpentinized.

tacts between the units are rare, and field studies have confirmed that most changes from one type to another take place over a narrow transition zone.

Peridotite

The peridotite unit is an olivine cumulate that occurs as a 75- to 100-meter-thick layer-like envelope. It appears to overlie a narrow mass of olivine gabbro to the east that is either a keel-shaped feeder conduit or has been separated from the similar central troctolitic rocks by faulting. Internal structures within the peridotite indicate that it is dipping west at a low angle.

The rocks of this unit are dark gray to black and weather to a rusty brown color. Serpentinized cumulus olivine and minor magnetite are enclosed in large irregular pyroxene and plagioclase oikocrysts that appear to be entirely post-cumulus. Olivine grains average about 1.2 mm in diameter and are euhedral when enclosed entirely by plagioclase or pyroxene. When they are in contact with other olivine grains, they show the typical curving boundaries and 120° triple contact points between three grains. A typical texture is shown in Figure 4d.

Modal composition of the peridotite varies considerably, as shown by two extreme examples in Table 1. Compositions of olivine have been obtained by $2V$ determinations and are on the order of Fo 80. Compositions of pyroxenes are also given in Table 2 and Figure 5 and plagioclase in Figure 6. Note that the plagioclase is all intercumulus and ranges in composition from An 80 to An 65. This zoning is probably due to the fact that the intercumulus phases crystallized from a trapped liquid of limited volume.

The texture indicates that this unit was formed while olivine and magnetite were the only solid phases and were nucleating abundantly. Plagioclase and pyroxene are postcumulus, filling small intercumulus voids, and were thus not stable above the floor of the magma chamber. The large grain size of the pyroxene and plagioclase indicates the small degree of supersaturation of these phases even in the intercumulus volume. The rocks are interpreted to be mesocumulates whose formation involves a considerable period of olivine adcumulus growth. At some point the intercumulus liquid became trapped, terminating the equilibrium with the overlying liquid.

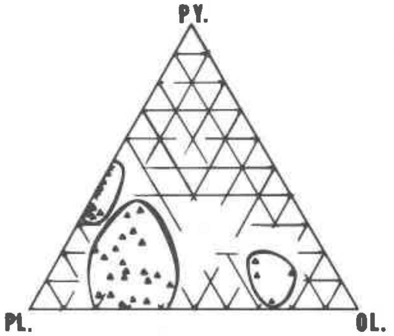

Fig. 3. Partial modal compositions of three major rock types: 4 olivine cumulates (peridotite); 21 bytownite troctolites and gabbros; 8 labradorite quartz gabbros. The separation between the olivine-bearing gabbros and olivine-free rocks is made on the basis of texture as well as mineral content.

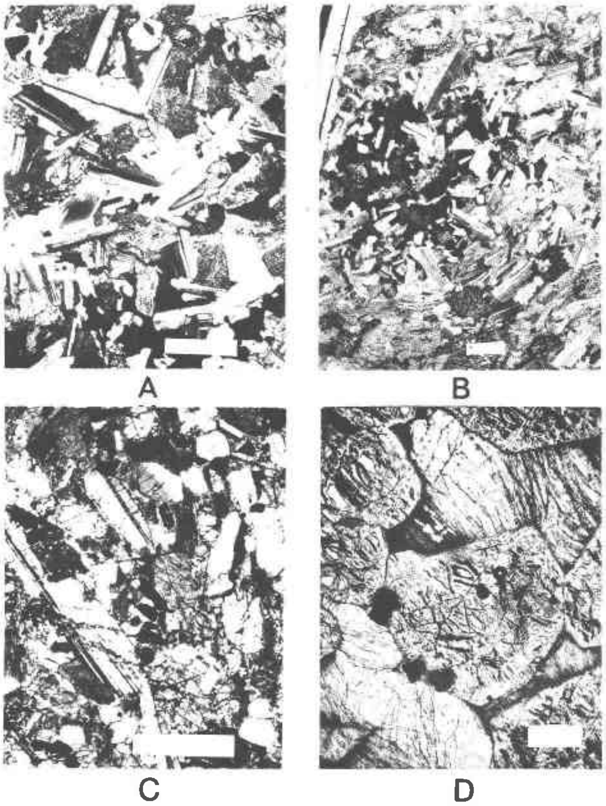

Fig. 4. (A) Labradorite gabbro showing granular texture resulting from cumulus nature of pyroxene; bar = 2 mm. (B) Large poikilitic pyroxene in bytownite gabbro shown enclosing euhedral plagioclase and with concentrically oriented plagioclase about the circumference of the poikilocryst; bar = 5 mm. (C) Bytownite troctolite showing large amounts of serpentinized olivine and resulting tension fractures in the plagioclase; bar = 5 mm. (D) Peridotite or olivine cumulate; note overgrowth of olivine about embedded euhedral magnetite; bar = 1 mm.

Troctolite

This plagioclase–olivine-rich rock comprises the large central part of the intrusive. It overlies and is surrounded largely by the peridotite and grades upward into the quartz gabbro to the west. All of the

Table 2. Optical properties and compositions of minerals

Sample Number	Rock Type	2V	β index	Composition
Orthopyroxenes				
W-22	Ultramafic	76°	-	En. 80
W-74	Ultramafic	78°	-	En. 82
W-204	Ultramafic	75°	-	En. 79
W-9	Troctolite	75°	-	En. 79
W-39	Troctolite	75°	1.684	En. 79
W-115	Troctolite	70°	-	En. 76
W-206	Troctolite	76°	-	En. 80
W-3	Gabbro	60°	-	En. 68
W-6	Gabbro	62°	-	En. 70
W-23	Gabbro	60°	-	En. 68
W-166	Gabbro	63°	1.688	En. 72-76
Clinopyroxenes				
W-74	Ultramafic	57°	1.678	En. 49 Wo. 46 Fs. 5
W-39	Troctolite	49°	1.686	En. 46 Wo. 40 Fs. 14
W-115	Troctolite	54°	-	
W-125L	Troctolite	51°	-	
W-166	Gabbro	53°	1.684	En. 46 Wo. 44 Fs. 10
Olivine				
W-61	Ultramafic	87°		Fo. 79
W-74	Ultramafic	90°		Fo. 85
W-204	Ultramafic	88°		Fo. 81
W-9	Troctolite	87°		Fo. 79
W-206	Troctolite	85°		Fo. 75
W-125	Troctolite	89°		Fo. 83
W-115	Troctolite	84°		Fo. 73

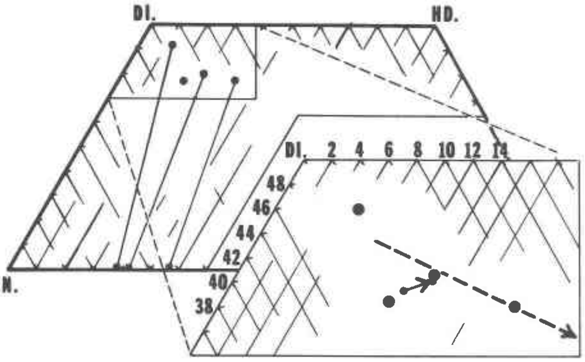

Fig. 5. Plot of pyroxene compositions, based largely on optical data. The inset shows clinopyroxene data including a compilation of several electron microprobe analyses of the oikocrysts from sample W-39. One of these is given in Table 3. The arrow indicates the variation in composition. The average of rim analyses (head of the arrows) is slightly richer in iron and calcium than the centers of the oikocrysts (tail of arrows), but the variation is small and one reversal of this trend was observed. In the main diagram the line on the left is sample W-74, an ultramafic; the center one W-39, a troctolite with large oikocrysts of clinopyroxene; that on the right is sample W-166 which is gabbro with granular texture.

troctolites are plagioclase–olivine cumulates, and they contain varying amounts of poikilitic pyroxene.

Plagioclase and olivine are anhedral, so that the texture is best described as allotriomorphic and indicates considerable adcumulus growth. Grain size is about 2 mm except for the pyroxene, which is from 1.5 cm to 3.0 in diameter. Figures 4b, c and Figure 7 illustrate these textures at different scales. Both plagioclase and olivine are extensively altered, particularly olivine, which may be up to 80 percent serpentinized. Plagioclase contains fractures localized between olivine grains. This illustrates how serpentinization placed considerable stress on the minerals surrounding the olivine (Fig. 4c).

Composition of the olivine is similar to that in the peridotite, ranging between Fo 75 and Fo 80. Plagioclase compositions obtained by the 5-axis universal stage method of Noble (1965) are shown in Figure 6. The inset showing compositions of cores and rims indicates compositional zoning in individual grains is moderate, generally less than 10 mole percent. As in the case of the peridotite, the anhedral textures and

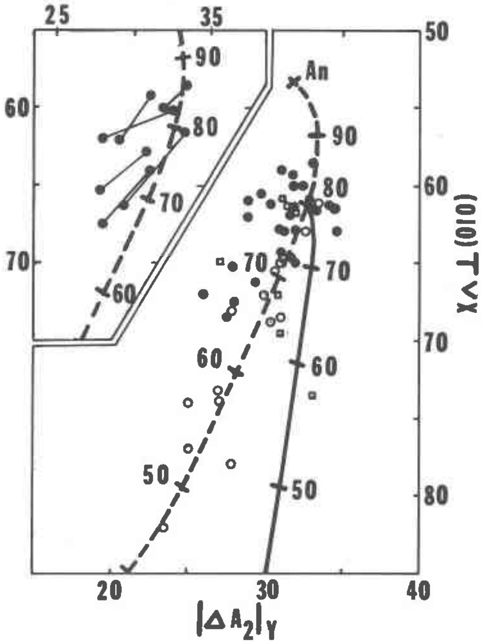

Fig. 6. Plagioclase compositions determined by the method of Noble (1965). The parameters measured are angles between indicatrix and crystallographic directions. Compositions of plagioclase are shown along the curves. The dashed curve is for plutonic plagioclase. Open squares are from the peridotite, solid circles from the troctolite and olivine gabbro, and open circles from the quartz gabbro. The inset shows the plutonic curve between An 60 and An 90. The connected points are from cores and rims of plagioclase crystals demonstrating the extent of zoning. Zoning is always normal so cores are always more calcic.

slight compositional zoning suggest slow adcumulus growth of these phases. Pyroxene compositions are shown in Figure 5 and an electron microprobe analysis in Table 3. Again they are very magnesian, and zoning is limited. The compositional range of a single oikocryst determined by electron microprobe analysis is shown by the arrow in the inset. This range is approximately the error of the analysis and is not considered to be significant.

Figure 3 and the modes of Table 1 illustrate that pyroxene content ranges from nil to nearly forty percent in this unit. A series of modes taken across a pyroxene-rich layer (Fig. 8) shows that the plagioclase-to-olivine ratio is nearly constant with a value of 2.3, and that any variation in modal content is due only to changes in the abundance of pyroxene. Poikilitic clinopyroxene enclosed plagioclase and olivine early, as shown by the fact that the enclosed grains are smaller, more euhedral, and less altered than those crystals that are not enclosed (Figs. 4b,c, 7b). Figure 4c shows an additional textural feature, the tangential arrangement of plagioclase around the oikocrysts. These features, combined with the observation that the oikocrysts are occasionally found as layers, provide evidence as to their origin. Figure 7b shows only a portion of an oikocryst, and illustrates how the included crystals are rarely in contact with one an-

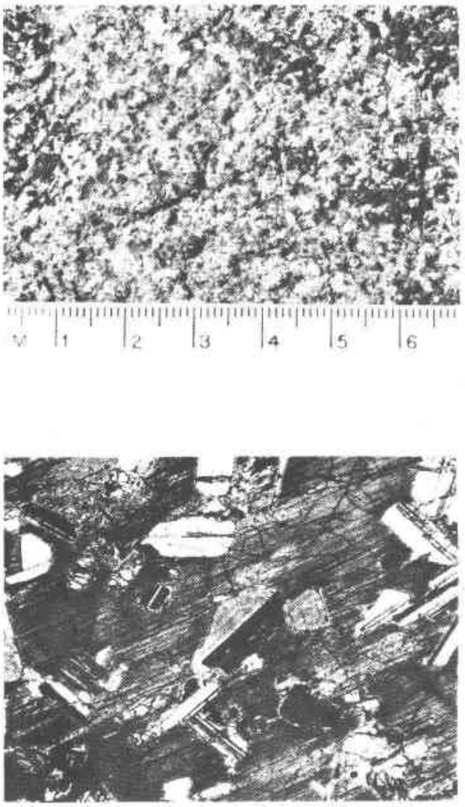

Fig. 7. Upper: photo of weathered surface of troctolite showing poikilitic pyroxenes. Lower: detail of oikocryst showing relationship between enclosed crystals and enclosing pyroxene; width of photo, 1 cm.

Table 3. Electron microprobe, partial analyses of the core portion of a poikilitic pyroxene specimen W-39 (same rock as shown in Fig. 4c)

Oxide	Weight Percent
SiO_2	52.93
TiO_2	0.69
Al_2O_3	2.24
CaO	20.48
MgO	17.70
FeO	7.13
Relative Numbers of Ions Based on 6 Oxygens	
Si	1.948
Al (Tet)	0.067
Al (Oct)	0.029
Mg	0.959
Fe	0.217
Ti	0.019
Ca	0.797
En	48.59
Fs	10.98
Di	40.41

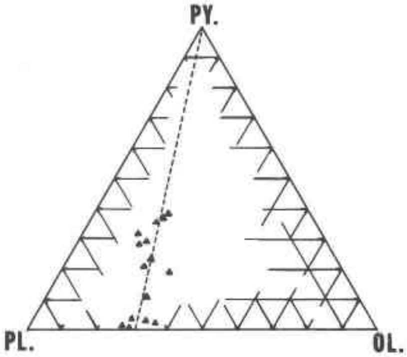

Fig. 8. Variation of modal composition between a pyroxene-rich and pyroxene-poor layer. The layers are actually quite distinct rather than gradational as shown. These data were collected modal analyses of 15 thin sections. The constant plagioclase/olivine ratio demonstrates that the only variable is pyroxene content (see text for interpretation).

other. This texture is similar to that shown by Wager and Brown (1967, p. 258, Fig. 141) as an example of a primocryst. All these textural features combine to indicate that the oikocrysts grew for the most part above the floor of the intrusion and settled to their present position. The difference between the habit of the plagioclase and olivine and the pyroxene oikocrysts is seen as a function of their respective growth rates.

Gabbro and quartz gabbro

Near the western end of the intrusion, the troctolite grades rather abruptly into gabbro and ultimately quartz gabbro. This change is the result of the loss of modal olivine, and is attended with a change in the clinopyroxene from poikilitic to a more granular habit. This results in a change in the texture of the rock to what is best described as subophitic or granular. Table 1 gives modes of three of these rocks, and shows the range of variation from rocks that appear just saturated to a quartz gabbro in which intercumulus granophyric material is common. Grain size is in the range of 0.75 mm to 1.0 mm, which is somewhat smaller than in the other units. Plagioclase is often oriented to form a fluxion texture. In contrast to the other units, the plagioclases are euhedral and display zoning over a range of An 80 in the cores to An 45 in the rims. The smaller grain size and zoning combine to suggest a greater degree of supersaturation of all the phases in this unit. An exception to this is postcumulus orthopyroxene, which often occurs as large poikilitic crystals.

Mineral compositions

Plagioclase

Plagioclase compositions and their thermal states were determined by the 5-axis universal stage method of Noble (1965). The values are plotted in Figure 6. Each point represents the average of several determinations obtained from a particular specimen. For the points in the main part of the diagram, no particular effort was made to focus attention on any part of the crystal; extinctions that seemed to represent the majority of the observed area were used. The values presented in the inset plot the same optical parameters, but only the plutonic (dashed) curve is shown. These values represent determinations of cores and rims from several troctolitic specimens. The core values are always more calcic than the rims. Evident in both parts of the diagram are the spread of the points and the impression that they may cluster to the left of the curve. This may indicate that revision of the curve is necessary.

The open squares are values taken from the postcumulus plagioclase in the peridotite. Their spread along the plutonic curve is shown. Compositions are obtained by dropping a perpendicular to the curve. Note that the peridotite values range from An 80 to An 65. As much of the plagioclase in the peridotite is altered, a relatively small number of values were obtained. As the plagioclase in the peridotite is poikilitic and crystal boundaries were not observed, it is possible that zoning could be greater.

Solid circles represent values from the troctolitic zone. Values range from about An 85 to An 65, but zoning observed in a given specimen is rarely more than about 10 mole percent, as shown in the upper left inset. The plagioclase in these rocks is generally anhedral and the zoning is of a continuous nature, suggesting extensive adcumulus growth.

Contrasted with the troctolitic plagioclase, that from the granular gabbros is euhedral, zoning is more apparent, and they are less calcic. Compositions range from An 80 in the cores to as low as An 45 on the rims.

Olivine

Olivine compositions have been determined by measurements of $2V$ with the universal stage and the curves of Deer *et al.* (1962, p. 22). Only values resulting from direct measurement between optic axes were accepted. In every case several measurements were made on the same crystal to ensure precision. Because of the high values of $2V$ it is difficult to obtain more than a few values from each rock-type, and variation existing in similar examples is disconcerting. When all of the values of Table 2 are noted it is apparent that limited iron enrichment has taken place.

As noted earlier and illustrated in Figures 4b,c,d, the olivine has been largely serpentinized. It is a cumulus phase throughout its crystallization period, which ends approximately with the appearance of the granular gabbro. This coincides with the change of clinopyroxene habit from poikilitic to subophitic and granular.

Pyroxene

Clinopyroxene compositions have been obtained by measurement of the beta index, and $2V$ with the

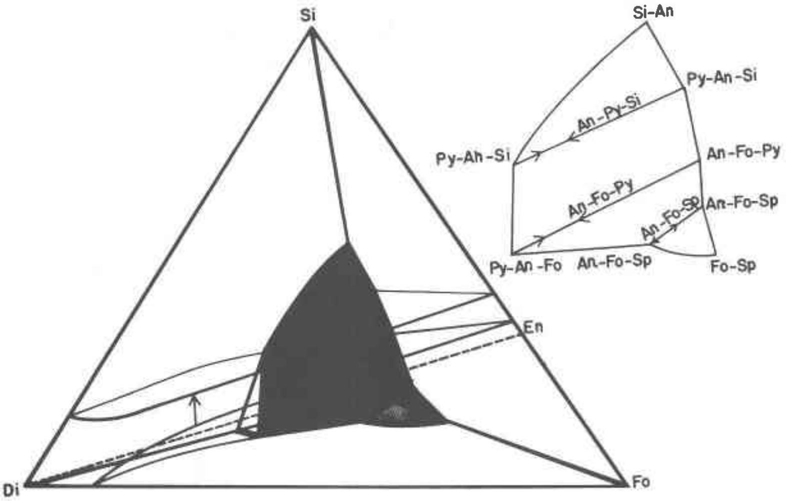

Fig. 9. The system Fo–Di–An–SiO_2 after Osborn and Tait (1952). The inset shows phase details of plagioclase saturation surface.

universal stage, using the curves of Hess (1949). Again only limited iron enrichment is evident.

The development of spectacular oikocrysts in the troctolite and the abrupt change to granular habit in the gabbro provide an opportunity to study the ophitic and related textures. The oikocrysts appear to have a complex history. In their centers the included crystals do not touch (Fig. 4b, 7b), while they are much more tightly packed on the rims (Fig. 4b). This suggests that the cores formed as primocrysts, as noted earlier, and the rims might represent continued, post-cumulus growth after the composite primocrysts of pyroxene and included crystals settled to the floor. If this represents the correct course of events, the oikocrysts would be expected to be compositionally zoned. The results of an electron microprobe study are shown in the inset of Figure 8. Slight enrichment in iron is apparent in most samples, indicating some magma evolution during growth of the oikocrysts. This combined with textural evidence is strongly suggestive of a dual history in the pyroxenes. An analysis of one of the oikocryst cores is given in Table 3. This analysis is typical of diopsidic augites from mafic intrusions.

Orthopyroxenes are all interpreted as being post-cumulus. They usually rim olivine in the peridotite and troctolite and are poikilitic in the quartz gabbro. Compositions have been determined by $2V$ measurements on the universal stage and in two cases by beta index determinations, by using the curves of Deer *et al.* (1963, p. 28). Orthopyroxenes also show some enrichment in iron in the gabbro, but none are sufficiently iron-rich to have inverted from pigeonite and hence show only the lamellar exsolution labeled as Bushveld type (Hess, 1960).

Composition trend based on mineralogy

The order of appearance of the major phases of the Rearing Pond intrusion has been established by this petrographic study to be olivine, plagioclase, clinopyroxene, and orthopyroxene. This sequence is interpreted from the four major rock types: peridotite, troctolite, olivine gabbro, and gabbro. This order can be described in the quaternary system Fo–An–Di–SiO_2, which provides some information on the composition of the initial magma as compared with magma compositions that have been proposed for the Keweenawan, Lake Superior province. The phase diagram in this system is also helpful in explaining the observed textural changes.

Particular attention is drawn to the differences in clinopyroxene habit between the earlier units, in which it is poikilitic, and the quartz gabbro, in which it is intergranular. This major change is correlated with the termination of olivine crystallization, and is due to an important change in the kinetics of clinopyroxene nucleation and growth at that point.

Figure 9 illustrates the system Fo–An–Di–SiO_2 after Osborn and Tait (1952), and Figure 10 represents a surface of "anorthite saturation" within that system. The surface is located at a composition of approximately 50 weight percent anorthite and is roughly parallel with the opposite side of the tetahedron (see Coombs, 1963). The arrow in Figure 10 shows a path of liquid evolution proposed for the Rearing Pond intrusion. The arrow implies the order

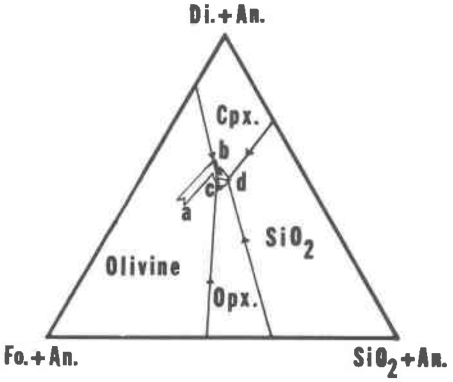

Fig. 10. Surface of anorthite saturation from the quaternary system in Fig. 9. Temperatures have been omitted but the detail improved over that shown in Fig. 9 from a number of sources, the major difference being the division of the pyroxene field in two parts. The spinel field has been omitted. The open arrow shows the course of fractionation. Anorthite always accompanies the phase shown in each section of the surface. a to b represents troctolite, b to c represents troctolitic or olivine-rich gabbro containing clinopyroxene oikocrysts, and c to d is a gabbro containing clinopyroxene of granular habit. d is the quaternary invariant point at which a silica polymorph begins to crystallize.

of crystallization of olivine and plagioclase, clinopyroxene, orthopyroxene, silica. Different segments of the arrow represent the different mineral assemblages on the liquidus.

Path a–b represents the period during which only olivine and plagioclase are in equilibrium with the liquid. Prior to the arrival of the liquid composition on the plane olivine crystallized alone, as is shown by the peridotite. Path a–b, then, represents the troctolite, in which olivine and plagioclase are cumulus. At point b clinopyroxene joins plagioclase and olivine, and the path changes direction toward the invariant point at c. At that point the peritectic reaction

forsterite + liquid = clinopyroxene + orthopyroxene

eliminates olivine as an equilibrium phase (Kushiro, 1972). This also represents the point in the intrusion where clinopyroxene changes habit from poikilitic to equigranular.

Path c–d is the region in which plagioclase, clinopyroxene, and orthopyroxene coexist with the liquid, and at invariant point d a silica phase joins them. From point c onward the path represents the granular gabbros, including the quartz gabbro of the western part of the intrusion. While this path has not been documented with rock analyses, the mineralogy requires that point d was attained at least in the intercumulus liquid of the gabbro. The strong iron enrichment that typically parallels this path is not observed in the Rearing Pond intrusion. This is evidently the result of early crystallization of magnetite, as observed in the peridotite.

Interpretation of the textures

One of the purposes of this paper is to describe and explain the textural variation that appears to be strongly related to the habit of clinopyroxene. The linking of this change in texture with cessation of olivine crystallization relates it to the peritectic point c of Figure 10. This point represents an abrupt change in the relative rates of growth and nucleation in clinopyroxene. This may be a manifestation of a change in the kinetics of crystallization of clinopyroxene, *i.e.* crystallization of olivine + plagioclase + clinopyroxene is somehow different from crystallization of plagioclase + clinopyroxene + orthopyroxene. Alternatively it may simply be a matter of the composition of the liquid relative to the field boundaries and the degree of compositional supersaturation that occurs under varying circumstances. These alternatives are not independent of one another and in fact are probably closely related.

If this is an important textural relationship, it must have been observed elsewhere in similar cases where fractionation of olivine has moved the liquid from olivine-normative to olivine-free composition. A further generalization might be that the textural change may involve either calcium-rich or calcium-poor pyroxene. No observations were made to support or refute such a generalization. The following descriptions are included as a sampling of other studies in which similar observations have been made.

Krokström (1932) studied several Swedish dolerites and basalts, including the Breven dike, and noted that the ophitic texture was well developed only in olivine-bearing rocks. Similarly, Walker (1957) reported, in a study of a large number of basaltic intrusive rocks from the Karroo series, the Palisades sill, and Scotland, that the olivine-bearing rocks are more often ophitic while those poor in or lacking olivine (tholeiitic) are usually subophitic. Walker (1969) described the lowermost dolerites in the Palisades sill as subophitic to intergranular and lacking olivine. Contrasting with this, the "hyalosiderite dolerite" of the well-known olivine layer is described as gabbroic and poikilitic in texture, while the cessation of olivine marking the top of the layer is accompanied by a corresponding change back to the subophitic texture. The grain size of plagioclase and pyroxene is described as about the same in these rocks. The higher rocks in the intrusive are olivine-free and subophitic.

Contrasted with the subophitic and intergranular rocks of the Palisades are the chilled marginal rocks of the Skaergaard intrusion (Wager, 1961), which contain modal olivine and poikilitic pyroxene. Detailed descriptions of the Skaergaard textures show that while olivine is a stable phase (cumulus mineral), the pyroxenes are poikilitic (ophitic texture) without regard for the distance from the border of the intrusive (Wager and Brown, 1967, p. 68–71, 106–122). On the other hand, in the layered series the middle zone (MZ) is characterized by and distinguished from the lower zone (LZ) by (1) the absence of olivine and (2) the abundantly nucleated pyroxene (Wager and Brown, 1967, p. 68–74). Further, these authors note (p. 71) that clinopyroxene is cumulus in the lower zone (LZ) but with poikilitic habit. Indeed the boundary between the LZ and MZ is based on the cessation of olivine crystallization, and this is approximately the point where pyroxene appears to begin to nucleate abundantly. The observation in the Skaergaard intrusion is that the chilled marginal rocks are olivine-bearing and ophitic, as are the presumably more slowly cooled olivine-bearing rocks of the lower layered zone, while the equally slowly cooled olivine-free rocks of the middle layered zone are of intergranular texture.

In a detailed study of two contrasting dikes, Gray (1970) found that a quartz tholeiite dike in Grenville Township, Quebec displayed intergranular texture at the edge and was still subophitic 10 m from the edge. On the other hand, the texture of an olivine gabbro dike at Kigaviarluk, Baffin Island changed from granular at the edge to ophitic 10 m inward from the edge. Gray noted this relationship as well as that noted above by Walker (1957) as indicating that silica saturation played an important role in controlling textures of basic rocks.

These observations support the notion that the presence or absence of olivine somehow controls the nucleation and growth rate of the pyroxene. Most of the analyses of textures in the geological literature related nucleation rate to the degree of undercooling (Wager, 1961; Oppenheim, 1964; Gray, 1970; Carmichael *et al.*, 1974, p. 149–156; Kirkpatrick, 1976), but in the examples cited here the change in nucleation rate, while related to cooling rate, is more closely dependent on the changes in phase relationships between olivine and pyroxene. That is not to say that rate of cooling is unimportant. Clearly the examples of the Skaergaard chilled marginal rocks and the dikes of Gray (1970) illustrate well the effect of the rate of cooling on grain size of the same rock composition. It is interesting that in the chilled margin of the Skaergaard intrusion olivine was most affected by the change in cooling rate, actually becoming large enough to poikilitically enclose much of the plagioclase (Carmichael *et al.*, 1974, p. 168).

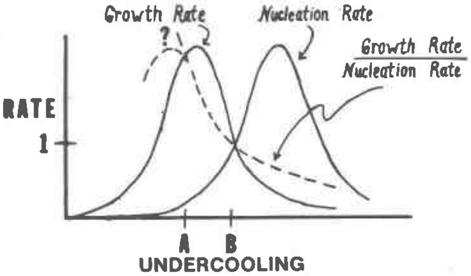

Fig. 11. Nucleation and growth rates *vs.* undercooling. The dashed lines represent the growth to nucleation rate ratio as suggested by Shaw (1965). Whether the dashed curve continues to rise or falls at small undercoolings depends on whether growth or nucleation goes to zero first as undercooling decreases. See discussion in text.

A number of workers have studied the implications of the theories of nucleation and growth rates with cooling on the textures of igneous rocks (Shaw, 1965; Gray, 1970; Carmichael *et al.*, 1974, p. 147–168; Dowty *et al.*, 1974; Kirkpatrick, 1976). While there are some experimental data on nucleation and crystal growth in silicate systems (Kirkpatrick, 1974; Lofgren, 1974; Donaldson, 1976; Fenn, 1977), most arguments are based on the application of theory to observations of natural systems. Shaw (1965) has discussed such applications, emphasizing the importance of the ratio of the growth rate to nucleation rate, particularly at small undercoolings. Plots of nucleation and growth *vs.* undercooling are shown in Figure 11. These are only qualitative, so they are deliberately drawn with maxima of equal height. The dashed curve is the growth to nucleation rate ratio, as suggested by Shaw. While olivine is crystallizing with clinopyroxene (the condition illustrated by curve BC of Fig. 10), the supersaturation in pyroxene might be kept small, *i.e.*, left of point A in Figure 11; when olivine is no longer crystallizing the supersaturation of pyroxene may increase, to point B or more. The experimental studies cited by Carmichael *et al.* (1974, p. 164), suggest the difference between the peaks in terms of temperature could be as small as 25°C. Such a change in supersaturation could be sufficient to change the texture from ophitic to subophitic or even intergranular.

The habit change of clinopyroxene in the Rearing Pond intrusion appears to represent such a change in the growth to nucleation ratio in response to changing phase relationships. While the liquid composition is on the curve joining clinopyroxene and olivine, clinopyroxene nucleates slowly but grows relatively rapidly. Several mechanisms may operate with equal or varying degrees of effectiveness to slow the nucleation of the last phase to become stable. If the relationship is of a cotectic nature the olivine and pyroxene will compete for components, which in effect reduces the amount of undersaturation that can occur. Data from Donaldson (1975) indicate that basaltic magma in the vicinity of the crystallizing olivine is less saturated in pyroxene components than at a greater distance from the olivine. This suggests that such a mechanism could decrease the supersaturation of pyroxene, which is the opposite of what might be expected from study of a phase diagram in which the liquid might overshoot a cotectic.

In contrast to the above situation, the nucleation rate of clinopyroxene becomes greater and growth rate apparently lower after the peritectic point (c of Fig. 10) is reached, when olivine is no longer stable. This results in greater supersaturation in pyroxene, so that the ratio of growth to nucleation rate becomes smaller. In every example considered, this mechanism would explain the simultaneous cessation of olivine and change to the subophitic or granular texture.

Calcium-poor pyroxene appears to be entirely postcumulus and occurs both with and without olivine, so no change in habit is recorded. It might be concluded that calcium-poor pyroxene never becomes sufficiently supersaturated to nucleate rapidly as the liquid composition passes from point c to d.

The large spectacular clinopyroxene oikocrysts of the Rearing Pond intrusion produce an extreme example of the ophitic texture common in many basic intrusive rocks. It has been shown that the ophitic texture is best developed in olivine-bearing rocks that have cooled slowly. This has been explained with classical theory relating nucleation rates and degree of undercooling. Typically the degree of undercooling or supersaturation has been related to cooling rate (Carmichael *et al.,* 1974, p. 168). The decrease in grain size associated with the margins of intrusive bodies demonstrates this. Alternatively it is shown here that olivine-bearing rocks are ophitic, while olivine-free rocks may be of granular texture. This is true in the case of the Rearing Pond intrusion, and has also been described in the Skaergaard intrusion and the Palisades sill in addition to several minor intrusions.

As the textural changes related to olivine occurrence seem to be more closely associated with changes in phase relationships than with chilling, it is proposed that this mechanism may be as important as oversaturation by chilling. In the chilled margin of the Skaergaard intrusion, the texture is ophitic even at the contact. On the other hand, most olivine-free dikes are granular even tens of meters from the contact.

The Rearing Pond intrusion illustrates the crystallization history which provided excellent conditions for the observation of this important textural change. While it was not possible to determine the initial liquid composition, the trends were made apparent through modal and mineralogical studies. The path began in the phase volume of olivine and a magnetite-rich spinel, moved into the plane of olivine and plagioclase, then to the four-phase boundary where clinopyroxene joined olivine and plagioclase. The slow nucleation rate of pyroxene resulted in the development of the spectacular poikilitic 'spots,' which were crystallizing directly from the primary magma, not from a trapped intercumulus liquid. The texture and lack of zoning support this. Finally, as the five-phase point where olivine reacts to form two pyroxenes is reached, the degree of saturation of clinopyroxene became great enough to allow abundant nucleation, and the texture changed to subophitic or granular. The mineral composition of these granular gabbros suggests that the liquid composition proceeded beyond the invariant point along the boundary joining the fields of plagioclase, clinopyroxene, and orthopyroxene. The presence of abundant intercumulus granophyric material is the strongest evidence in this regard. The relative increase in the degree of zoning in the plagioclase of these rocks may indicate an increased rate of crystallization of the feldspar as well. The general decrease in grain size suggests accelerated nucleation as well as growth rates but with markedly different effect on the pyroxene than on the plagioclase.

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