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CORRELATED CHANGES IN MINERAL ASSEMBLAGES AND IN ROCK HABIT AND FABRIC ACROSS AN ORTHOPYROXENE ISOGRAD, GRENVILLE PROVINCE, QUEBEC

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ABSTRACT. The orthopyroxene isograd, 75 km northeast of the center of the Morin Anorthosite, indicates the appearance of orthopyroxene in common quartz-bearing leucocratic rocks containing two feldspars. The *orthopyroxene zone* southwest of the isograd and extending at least to the Morin Anorthosite is characterized by the presence of orthopyroxene and one or more of clinopyroxene, hornblende, and biotite in such rocks. The abundance of hydrous mafic minerals increases toward the isograd. In the *hornblende zone* northeast of the isograd these rocks contain hydrous mafic minerals to the exclusion of pyroxenes.

Gradual changes in rock habit and fabric take place concurrently with the mineralogic change. From the orthopyroxene zone to the hornblende zone: (1) migmatites become more abundant, (2) grain size increases, (3) lenticular quartz grains disappear and are replaced by near-equidimensional grains, (4) dispersion of a pervasive subhorizontal mineral lineation increases from a well defined point maximum to a partial great circle. Mesoscopically folded lineations are virtually absent. Minor folds change in many respects but remain consistently recumbent and semi-isoclinal.

A comparative literature study of similar terranes leads to the conclusion that high-grade synkinematic metamorphism superimposed on a high-grade metamorphic sector of the Earth's crust can result in this pattern of gradual changes. Applied to the area under consideration, it is likely that early *prograde* metamorphism culminated in granulite-facies assemblages and was followed *uninterruptedly* by late paracrystalline deformation during incipient *retrograde* metamorphism.

The position of the orthopyroxene isograd and other similar isograds with respect to the Morin and Adirondack Anorthosites suggests a relation between orthopyroxene-grade terranes and these anorthosite masses. It is unlikely, however, that this relation is due to contact metamorphism.

INTRODUCTION

Few isograds have been mapped in the high-grade metamorphic terrane of the Grenville province (Canadian Shield) north and northwest of Montreal (fig. 1). There are the *"composite isograd"* drawn by Wynne-Edwards and others (1966) and the *orthopyroxene isograd* mapped by Schrijver (1966a). Three other "isograds" drawn by Martignole and Schrijver (1970a) are now considered to be related more closely to chemical bulk composition than to gradients in physical conditions. These last three "isograds" will not be considered in this communication.

It is not known with certainty whether the first-mentioned isograds are entirely independent of changes in bulk composition (of the anhydrous equivalents of the rocks concerned). One difficulty in ascertaining this independence is the fact that both isograds are subparallel to the strike of lithologic units. Furthermore, it is not known whether the two isograds are in continuity with each other because part of the intervening area has not been mapped. Nevertheless, the outstanding feature of the regional map pattern north and northwest of Montreal is that the two isograds outline an area, rudely centered on the Morin Anorthosite, in which orthopyroxene is a common mineral in many metamorphic rocks (fig. 1). The orthopyroxene-grade terrane so delineated has a surface

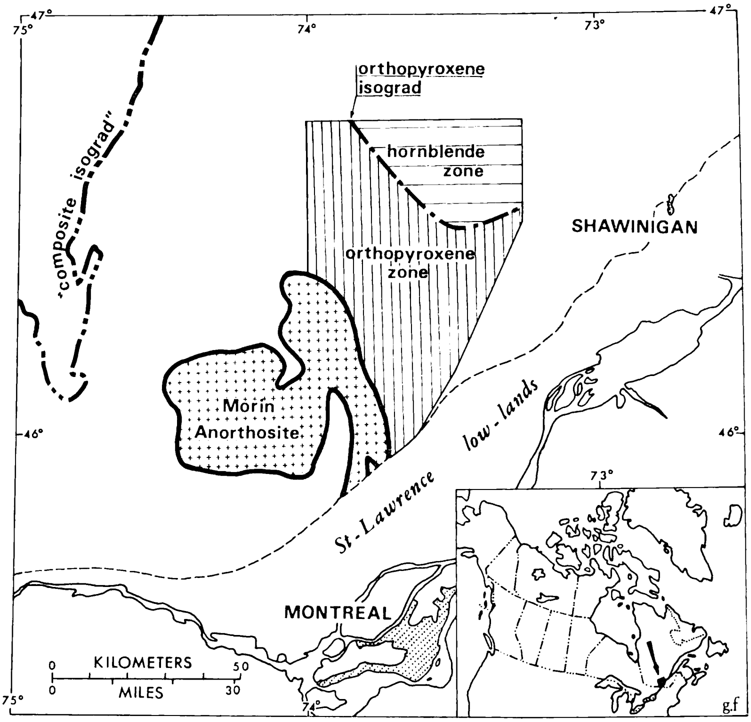


Fig. 1. Index map. "composite isograd" from Wynne-Edwards and others (1966).

area of at least 11,000 sq km. Approximately half this area is underlain by relatively homogeneous masses of coarse-grained meta-igneous rocks ("plutonites") ranging from anorthosite (Morin Anorthosite Mass: 2500 sq km) to mangerite and quartz-monzonite (Wynne-Edwards and others, 1966; Martignole and Schrijver, 1970a, pl. 1). The other half of the area is underlain by a heterogeneous interlayered assemblage of metasedimentary rocks (quartzites, garnet-sillimanite gneisses, crystalline limestones) and metamorphic rocks of unknown origin, predominantly leucocratic granulites and gneisses. We will be concerned mainly with a late stage in the metamorphic and structural evolution of this last category of rocks, regardless of its origin.

It is the prime purpose of this paper to describe the changes in rock habit and fabric that take place concurrently with the change in mineral assemblages across the orthopyroxene isograd. Secondly, with the aid of published descriptions of similar terranes, some temporal and genetic relations between the spatially correlated properties are outlined, and an hypothesis is formulated concerning an important part of the geological evolution of the area under consideration. Lastly, the role of the Morin Anorthosite and associated plutonic rocks in this evolution is considered briefly.

THE ORTHOPYROXENE ISOGRAD: CHANGE IN MINERAL ASSEMBLAGES

The area under consideration is approximately 3500 sq km and straddles the orthopyroxene isograd (fig. 1). Two thirds of the area belong to the "orthopyroxene zone", the remainder being in the "hornblende zone". One relatively homogeneous mass of coarse-grained mangerite and mangeritic augen gneiss occurs in the area (Lac-Croche plutonic Complex: Schrijver, 1968a, b; not shown in fig. 1). This meta-igneous complex underlies an area of 400 sq km and is confined to the orthopyroxene zone.

The orthopyroxene isograd, located at a minimum horizontal distance of 75 km from the center of the Morin Anorthosite, is based on the *appearance of orthopyroxene in common leucocratic rocks (color index 1 to 35) containing quartz and two feldspars.*

The *orthopyroxene zone,* situated south and southwest of this isograd and extending at least to the Morin Anorthosite, is characterized by the presence of orthopyroxene and one or, less commonly, two hydrous minerals (hornblende and biotite) besides potassic feldspar, plagioclase (commonly oligoclase), and quartz. Clinopyroxene is commonly present. Out of 90 specimens of such rocks collected in the orthopyroxene zone, 68 percent contain both anhydrous and hydrous mafic minerals, 20 percent contain exclusively hydrous, and 12 percent exclusively anhydrous mafic minerals. The rocks containing exclusively hydrous mafic minerals occur predominantly in ill-defined domains which do not seem to be mappable. Despite this irregularity in spatial distribution, the volume ratio of hydrous to anhydrous mafic minerals seems to increase rather gradually toward the isograd.

Textural evidence bearing on the sequence of recrystallization of hydrous and anhydrous minerals is ambiguous. Grain-to-grain contacts of pyroxenes and hornblende or biotite are common and suggest late growth of hornblende with respect to pyroxenes. The author considers this evidence insufficient for a more positive statement.

Compositionally roughly similar rocks in the *hornblende zone* contain hydrous mafic minerals to the exclusion of pyroxenes (see legend to pl. 2; also Martignole and Schrijver, 1970a, table 2). Exceptions to this rule have not been encountered. Accessory minerals of these rocks in both zones are iron(-titanium) oxides, apatite, and zircon. Garnet is rare but seems to be more common in the hornblende zone than in the orthopyroxene zone.

The isograd so defined can be bracketed within 2 km at right angles to its trend and can be followed for at least 38 km.

The mineral assemblages of common mesocratic rocks (color index between 35 and 65) do not show any obvious and consistent differences between the two zones. Most mesocratic rocks consist essentially of plagioclase (An_{25} to An_{40}: U-stage), hornblende, orthopyroxene, clinopyroxene, and biotite ("pyroxene-amphibolites"). Amphibolites without pyroxene account for about 7 percent of all mesocratic rocks. It is remarkable that according to the sample obtained (53 specimens from the orthopyroxene zone and 13 from the hornblende zone), this figure of 7 percent holds for both zones. Mesocratic pyroxene-plagioclase rocks are rare and occur exclusively in the orthopyroxene zone.

Pelitic rocks in both zones consist essentially of potassic feldspar, quartz, biotite, garnet, and sillimanite, with or without plagioclase (Martignole and Schrijver, 1970a, table 3). These rocks are considerably more abundant in the orthopyroxene zone than in the hornblende zone, so that possible differences in mineral assemblages cannot be assessed with the same confidence as those in more common rocks.

Crystalline limestones are too rare and too varied in mineralogy for a comparison between the two zones (Martignole and Schrijver, 1970a, table 4).

CORRELATED CHANGES IN ROCK HABIT AND FABRIC

In the "common leucocratic rocks . . . .", a number of changes take place in habit and fabric concurrently with the mineralogical change across the orthopyroxene isograd. Most conspicuous in the field is a change in degree and type of migmatization, whereas under the microscope a change in grain size is most remarkable. Furthermore, the type, direction, and degree of preferred form-orientation change markedly and gradationally across the orthopyroxene isograd.

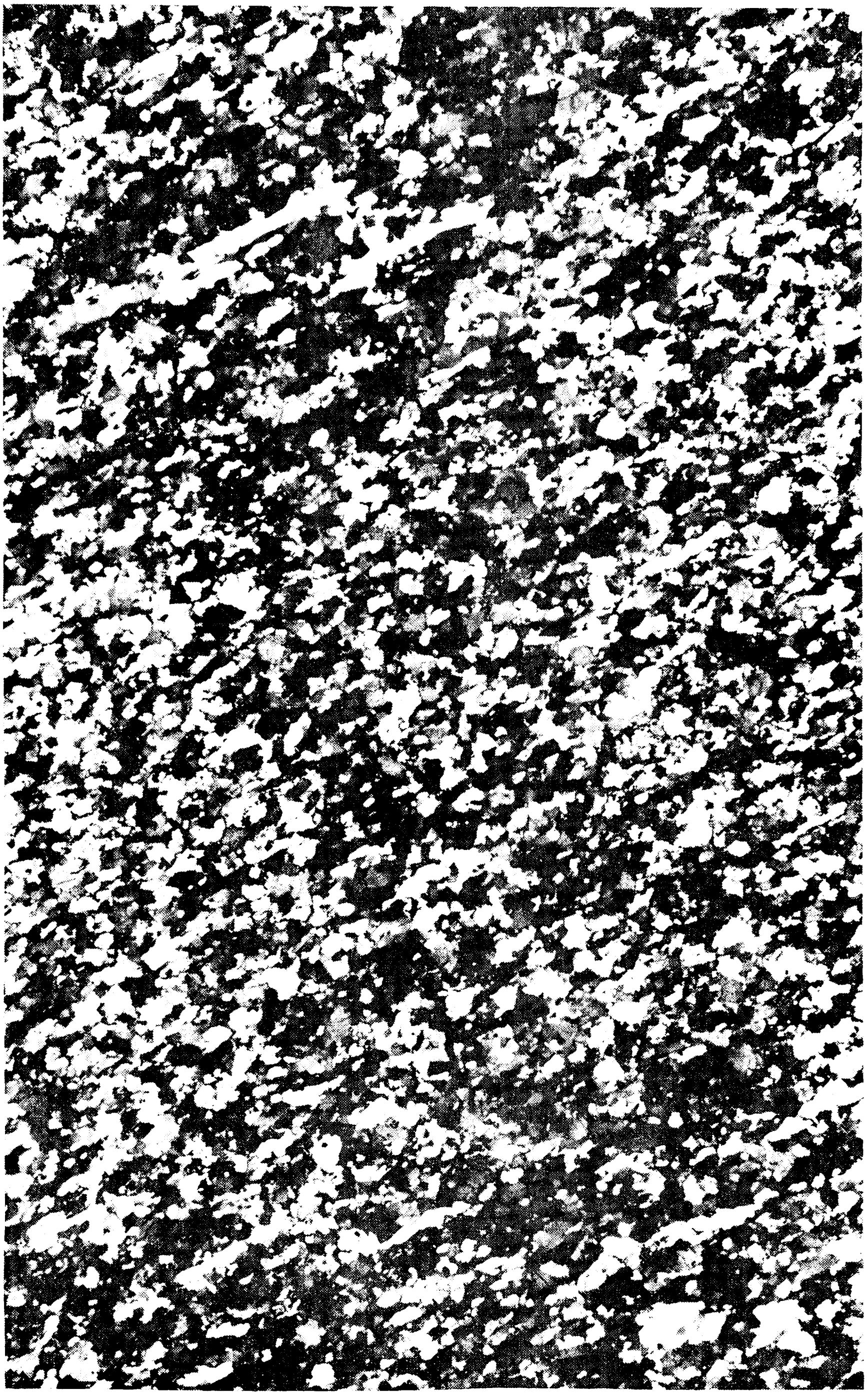
These changes take place over a distance considerably larger than the "zone of mineralogical uncertainty" around the isograd (2 km). Moreover, the width of the zone of gradation is different for each property. In any case, at a distance of at most 5 km southwest of the isograd one enters a terrane that is consistently and radically different from that at 5 km northeast of the isograd.

Before describing the changes in rock habit and fabric in some detail, it must be noted that the observations are of a qualitative nature only. Their reliability cannot be estimated quantitatively. However, the author believes that the geological conclusions arrived at would not be altered significantly by strictly quantitative work since (1) he was involved in the mapping of a large part of the area during four consecutive field seasons (Dimroth, ms; Schrijver, ms, 1966a, b), and (2) thousands of outcrops were studied in both zones during the field work. This must of necessity remain an assumption: quantitative work of the scope and scale of this report would be a life-consuming task.

The difference in *grain size* is easiest to illustrate: see plates 1 and 2. The grain size of a common leucocratic rock in the orthopyroxene zone ("granulite", pl. 1) is smaller than that of a typical leucocratic rock collected in the interior of the hornblende zone ("hornblende-biotite gneiss", pl. 2).

The plates also show clearly one other aspect of the change in fabric. The rock from the orthopyroxene zone contains a large number of *lenticular quartz grains* (which are considered to be characteristic of some "granulites"; see Behr and others, 1971). The hornblende-biotite gneiss does not contain quartz lenticles; its texture is interlobate eugranoblastic.

PLATE 1



Leucocratic granulite from orthopyroxene zone, collected 4 km south of orthopyroxene isograd (specimen C11-9). Minerals, in order of decreasing abundance: plagioclase–quartz–potassic feldspar–orthopyroxene–biotite–opaques–apatite–zircon. Crossed polarizors. Field of view 5 sq cm.

Here it must be emphasized that we are comparing rocks of roughly similar modal composition: the only obvious mineralogic difference between the rocks shown in plates 1 and 2 is the presence of anhydrous mafic minerals in the granulite and their absence from the hornblende-biotite gneiss. Plate 3 shows that rocks of radically different mineralogy commonly show radical differences in fabric within the same zone—in this case within the same thin section.

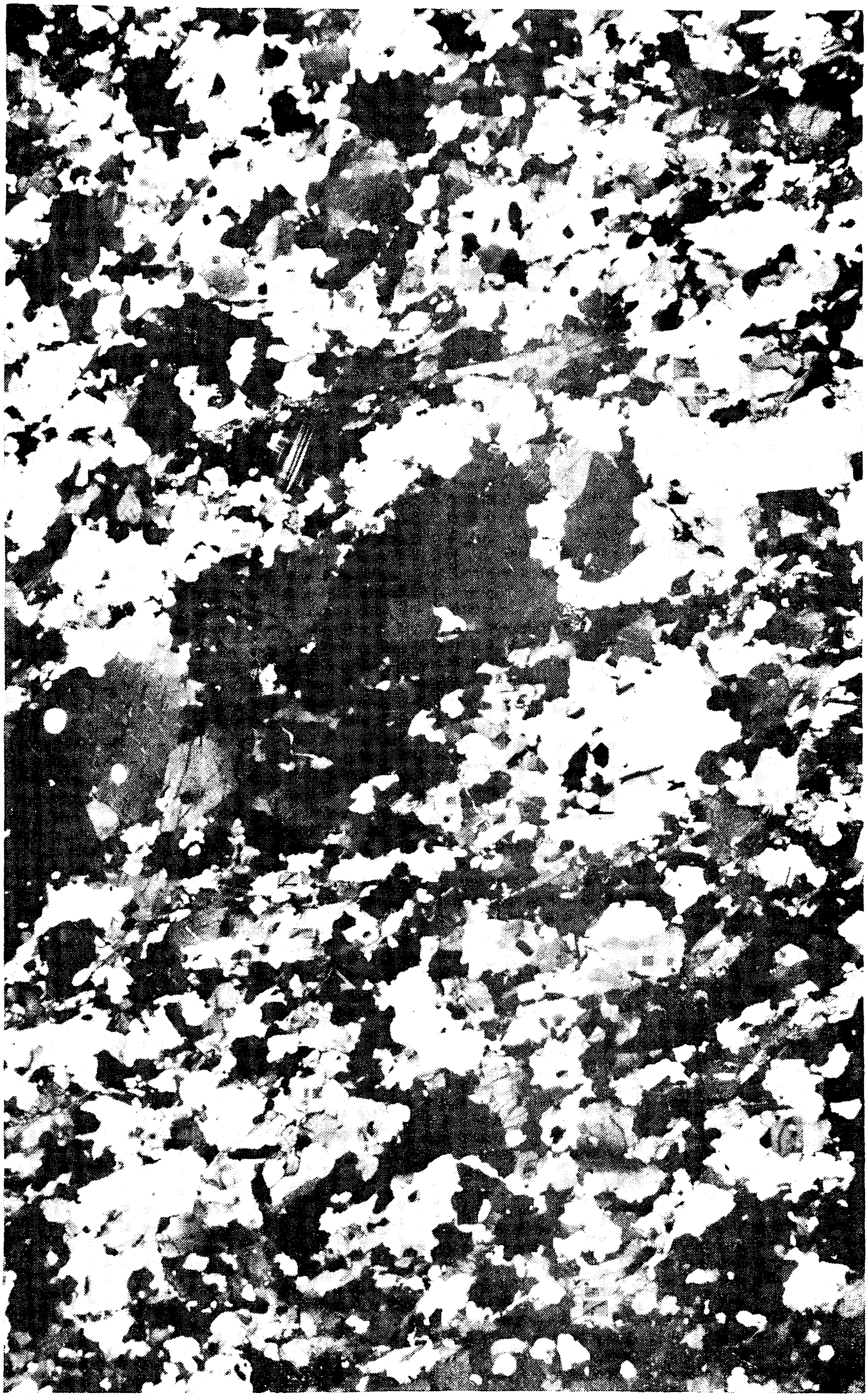
A comparison between plates 2 and 3 elucidates another remarkable difference between the hornblende zone and the orthopyroxene zone. The quartzofeldspathic lamina in the hornblende-biotite gneiss does not show an obvious preferred form-orientation whereas that in plate 3 is strongly oriented, mainly by form-oriented quartz lenticles.

The change in direction and degree of preferred form-orientation is documented in Martignole and Schrijver (1970a, pl. 2, subareas A to D): the *average orientation of a pervasive mineral lineation* changes gradually from a 7° plunge toward the north-northwest in the orthopyroxene zone (25 km southwest of the isograd) to a 16° plunge toward the east-southeast in the hornblende zone (15 km northeast of the isograd). Another significant change occurs in the *dispersion of the lineation,* from a well-defined point maximum in the interior of the orthopyroxene zone to an ill-defined maximum dispersed in a subhorizontal plane in the hornblende zone. Curiously, the great-circle pattern formed by this lineation is, to some extent, a property inherent to the hornblende zone; many small domains (single outcrops!) show a dispersion similar to that in the entire zone despite the *absence* of mesoscopically "folded" lineations. Furthermore, minor folds older than the lineation are extremely rare (only observed once), and minor folds distinctly younger than the lineation are very gentle and upright. Thus the dispersion is not due to superimposed folding but developed penecontemporaneously with the lineation itself (see however, Martignole and Schrijver, 1970a, p. 190-191).

Numerous minor folds with axes parallel to the pervasive mineral lineation occur in both zones. They are consistently recumbent to gently inclined and semi-isoclinal (Martignole and Schrijver, 1970a, p. 181-183). However, in other respects, the folds have a different habit in the two zones. In the hornblende zone a pervasive but diffuse subhorizontal gneissic lamination is present, usually making recognition of fold flanks impossible and recognition of fold hinges difficult (see Martignole and Schrijver, 1970a, fig. 29). Similar folds in the orthopyroxene zone do not have such an "axial-plane lamination" but show in their hinge zones at most a preferred form-orientation of quartz lenticles parallel to the axial planes. Laminae (and layers) are in fact present in the orthopyroxene zone, but they are commonly much sharper and better defined (pl. 3), and they are folded.

Here we have already touched upon the "most conspicuous" but, paradoxically, the most difficult-to-describe mesoscopic change, namely, that in *degree and type of migmatization.*

PLATE 2



Leucocratic gneiss from hornblende zone, collected 7 km northeast of orthopyroxene isograd (specimen K5-1). Minerals, in order of decreasing abundance: plagioclase–quartz–potassic feldspar–biotite–hornblende–opaques–apatite–zircon. Relatively coarse-grained lamina consists of potassic feldspar and quartz with minor plagioclase. Other parts of thin section consist essentially of plagioclase, quartz, biotite, and hornblende. Crossed polarizors. Field of view 5 sq cm.

In the interior of the orthopyroxene zone conspicuous migmatites are rare. However, the occurrence of mesocratic rocks as folded boudins embedded in a "matrix" of leucocratic rocks (quartzofeldspathic granulites) is suggestive of migmatites. Both "components" of these "migmatites" appear to have a common history of deformation and metamorphism; both take part in recumbent folds, and both may contain orthopyroxene. Also, both are lineated parallel to the fold axes by preferred form-orientation of most essential minerals (including orthopyroxene).

In the interior of the hornblende zone, migmatites are common. In fact, most "common leucocratic rocks. . . ." (that is, hornblende-biotite gneisses) may be considered to be migmatites consisting of alternating hololeucocratic laminae and laminae containing mafic minerals. Consisting of orthoclase, quartz, and minor plagioclase, the hololeucocratic laminae are coarser grained than the dark laminae (pl. 2). Moreover, they either show a poor preferred form-orientation of their constituent minerals, or they are not oriented at all. The dark laminae consist of plagioclase, quartz, hornblende, biotite, and opaque minerals. In "migmatite nomenclature" the hololeucocratic laminae would be called the "leucosome", whereas the dark laminae represent the "melanosome" (Mehnert, 1968).

Evidence of "progressive" migmatization is provided by irregular distribution of the leucosome blurring the gneissic lamination and thus forming "nebulites". Locally, in such strongly migmatized rocks, the grains are extremely coarse (for example, 3 cm), foliation and lineation are virtually absent, and the fabric is practically isotropic. Thus, in contrast with the relations in the orthopyroxene zone, migmatization outlasted pervasive deformation in the hornblende zone.

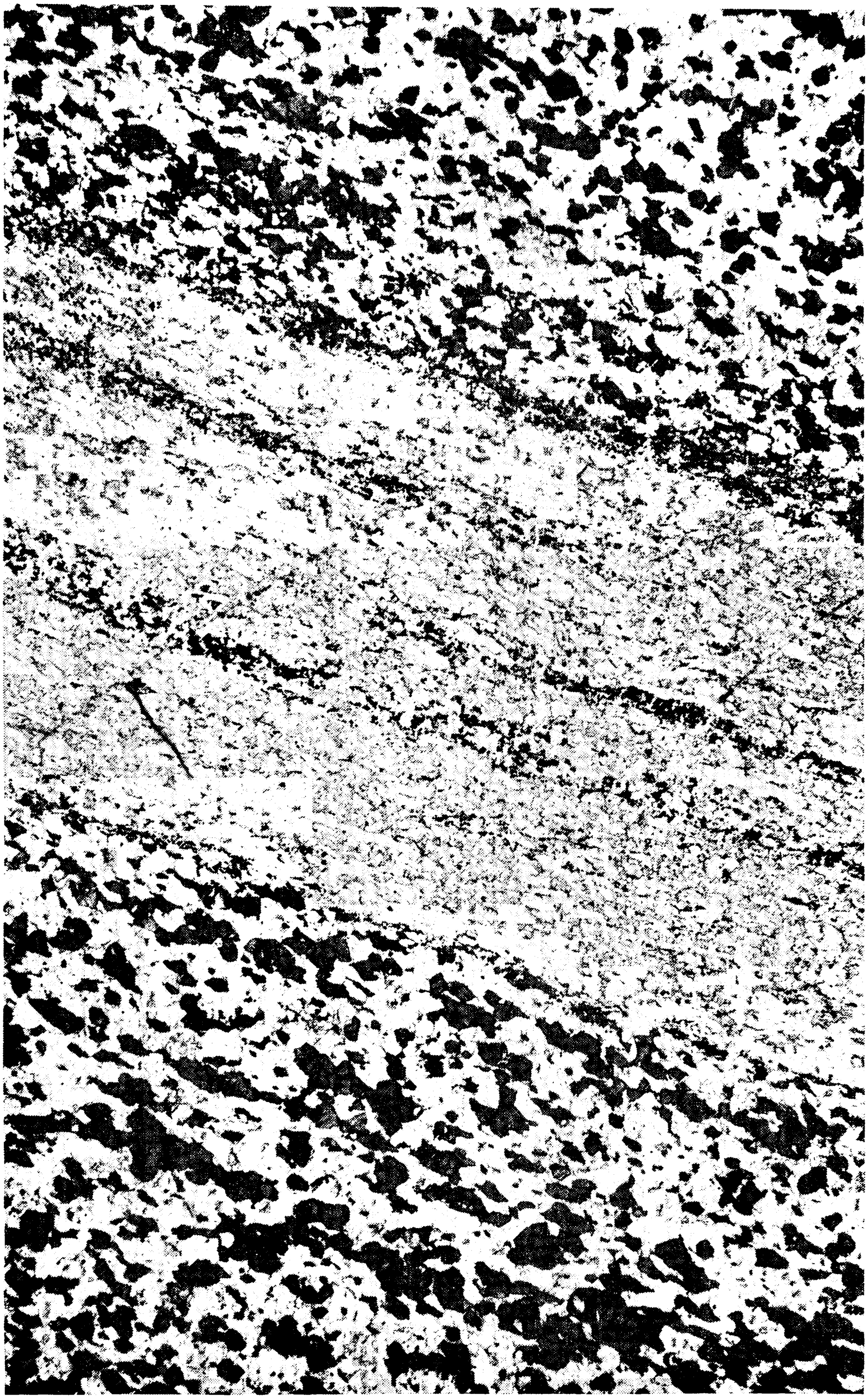
Amphibolites seem to be less abundant in the hornblende zone than in the orthopyroxene zone. The amphibolites present in the former are embedded in a leucocratic matrix (thus forming "agmatites") and occasionally line up in fold shapes. Curiously, within the amphibolite fragments, orthopyroxene is commonly present, whereas at their rims biotite and hornblende occur to the exclusion of pyroxenes.

Once more it must be emphasized that all changes in habit and fabric are *gradational but irregular*. Similar to the unpredictable occurrence of ill-defined "hydrous" domains within the orthopyroxene zone, domains of coarse-grained eugranoblastic granulites are present in the midst of "normal", relatively fine-grained, and well-oriented granulites. Again, some domains in the hornblende zone may show perfect parallelism of lineations instead of the common partial-girdle spread. Such anomalous domains range in size from a single large outcrop to perhaps 50 sq km. Most of these are not mappable at the customary scale of 1 mile to one inch (1:63,360).

SIMILARITIES AND DISSIMILARITIES FROM ELSEWHERE

To the author's knowledge, similar complete sets of relations have not been described in the geological literature of the past 20 years, but

PLATE 3



Laminated granulite from orthopyroxene zone, collected 23 km south of orthopyroxene isograd (specimen C3-12). Section shows alternating layers of plagioclase-pyroxene rock and quartzofeldspathic rock. Parallel polarizors. Field of view 5 sq cm.

perhaps they are not as rare as the literature tends to suggest. The near-impossibility of "explaining" the array of correlated properties is not conducive to ready publication! Moreover, it would seem that no single all-embracing hypothesis would be amenable to test by experimentation, calculation, or simulation. Therefore, any hypothesis in which account is taken of all or most changes described in this paper will necessarily be an inductive one. As such, its tenability will depend greatly on a comparative study of a number of terranes that are similar in at least a few respects to the one described above.

The author proposes to make such comparisons before offering an hypothesis concerning the specific, local problems.

Features strikingly similar to some of those north of Montreal have been described by Von Gaertner (1962) from northern Finnish Lapland. He writes (p. 208): "Northward, the granulites grade into hornblende-gneisses, garnet-amphibolites, and common amphibolites. Migmatic features increase markedly at a certain distance from the granulites. . . . The entire domain north of the granulite belt probably has been deformed homogeneously and repeatedly together with the granulites themselves. In any case, the northern parts crystallized and recrystallized under other conditions (water-rich) than the granulites."[1]

The excellent photographs in Von Gaertner's paper (pls. I and II) show pre- or synkinematic migmatites in the granulites and syn- or postkinematic migmatites in the hornblende gneisses.

Kranck (1936), in a description of part of the same area, stresses the subhorizontal foliation and lineation. In a schematic block diagram (1936, fig. 1), Kranck shows numerous gently inclined to recumbent, boudinaged minor folds.

A broadly similar description has been given by Cooray (1961, esp. p. 124-131) from a granulite-amphibolite facies terrane in Ceylon. He interprets the local relations as being the result of an episode of "granitisation and migmatisation" superimposed on the "structurally lower level" of a previously migmatized granulite-facies terrane.

Sutton, Watson, and James (1954, p. 61), in a report on an area in Tanzania, call upon "a front of migmatisation moving across a complex, parts of which had already reached the granulite metamorphic facies, and making such rocks over to a lower grade and more acid types".

The last two interpretations clearly stem from the "Read School of Granitisation", the founder of which gave an admirable review of related matters in his essay "Granite series in mobile belts" (Read, 1955).

Although most authors mentioned above refer in rather broad terms to differences in "tectonic style" between granulite- and amphibolite-facies terranes, the idea seems to originate with Wegmann (1929). He ascribed increasing dispersion of a single generation of lineations and fold axes to an increase in "mobility" of the rock material during deformation (see also Kranck, 1953). That an increase in this so-called "mobility" is strongly correlated with an increase in "syntectonic mig-

[1] Translation by K. Schrijver.

matization" has been shown convincingly by Mackenzie (1957) for a small amphibolite-facies terrane of the Moine Series (Scotland). The dispersion of lineations and fold axes is contained in a subhorizontal plane (see Mackenzie, 1957, fig. 3), similar to the relations in the hornblende zone north of Montreal.

Concerning grain size and quartz lenticles, it is instructive to consider an area where orthopyroxene- and hornblende zones are present and can be recognized as *not* having been affected by pervasive deformation subsequent to high-grade recrystallization. From the description by Binns (1964) it seems that these conditions are fulfilled in part of the Willyama Complex, Broken Hill District, New South Wales. Binns (1964, p. 285) writes, with respect to the episode of progressive regional metamorphism from amphibolite- to granulite facies ("Willyama Metamorphism"): "Products of the Willyama Metamorphism are relatively coarse grained (0.5-2.0 mm) and the different mineral constituents generally possess grain sizes of the same order.", and "Most Willyama Metamorphism products possess granoblastic textures indicative of equilibrium". These statements hold for (pyroxene-)amphibolites as well as for quartzofeldspathic rocks (compare Binns, 1964, fig. 13). Binns also notes (1) a progressive *increase* in grain size from the hornblende zone to the orthopyroxene zone (his orthopyroxene isograd is based on the first appearance of orthopyroxene in basic rocks), (2) a decrease in grain size where the Willyama Metamorphism products have been affected by later deformation and recrystallization, and (3) the rarity of migmatites in all metamorphic zones.

Workers particularly concerned with lenticular quartz grains in granulite-facies rocks commonly employ terms such as "granulation", "cataclasis", "(blasto-)mylonitization", et cetera. They thus refer to processes dominated by or involving mechanical disintegration. However, care must be taken in interpreting textural terms as illustrated by Katz's (1968) nomenclature and inference. He uses the term "cataclastic-gneissose fabric" but proceeds to affirm that "micro-brecciation or cataclasis sensu stricto" did *not* take place.

Whatever nomenclature is used (compare Moore, 1970), experimental work on quartz deformation (Carter, Christie, and Griggs, 1964, for example, pl. 10) tends to support the claim that relatively small well-oriented lenticular quartz grains are not necessarily due to mechanical disintegration but may form by plastic deformation and recrystallization of larger grains—even at strain rates obtaining in the laboratory.

From the literature it appears that the development of lenticular quartz grains in granulite-facies terranes is commonly ascribed to deformation superimposed on "dry" high-grade metamorphic rocks, either under granulite-facies conditions, or under amphibolite-, or even greenschist-facies conditions (for example, Hsu, 1955). In conjunction with the non-lenticular, near-equidimensional shape of quartz grains in quartzofeldspathic rocks of the Willyama Complex, this seems to be a plausible hypothesis.

AN HYPOTHESIS

Piecing together the facts and inferences contained in the last section, the author considers it unlikely that one episode of progressive regional metamorphism can result in the pattern of spatially correlated properties described in this paper—although we would need more studies like that by Binns (1964) to be quite certain about this. On the contrary, it seems reasonable to assume that *high-grade synkinematic metamorphism superimposed on a high-grade metamorphic sector of the Earth's crust* can result in such patterns.

To make this hypothesis more specific—more specific in fact than our knowledge of the local geology warrants—let us assume that an orthopyroxene isograd had been established, although not necessarily in its present position, prior to the last episode of high-grade synkinematic metamorphism. Then, during this last episode:

1. The relative abundance of H_2O in the hornblende zone would enable metatects to survive or metatexis[2] (synkinematic and/or postkinematic) to take place. On the other hand, the paucity of H_2O in the orthopyroxene zone would preclude any but very localized melting.

2. Lenticular quartz grains, if not already present, would tend to form in the orthopyroxene zone, whereas equidimensional grains would tend to form in the hornblende zone. Most other fabric differences between the two zones (grain size, dispersion of lineation) are equally well explicable in terms of this model.

3. Either the hornblende zone may have encroached on the orthopyroxene zone or vice versa. Either may account for the gradual increase in the abundance of hydrous minerals toward the present orthopyroxene isograd.

4. Adjustment of textures and mineral assemblages to cooling (and decompression) would have consisted essentially of solidification of metatects and partial or complete replacement of anhydrous by hydrous mineral assemblages, perhaps again affecting the position of the orthopyroxene isograd. The absence of pyroxenes near the interface of pyroxene-amphibolite fragments and leucosomes in the hornblende zone is probably due to this late, retrogressive metamorphism.

It is noted that there is no reason to assume that the present hornblende zone was at a "structurally deeper" (or shallower) level than the present orthopyroxene zone during this last episode of metamorphism. The shapes of the Morin Anorthosite (Martignole and Schrijver, 1970a, fig. 39) and the Lac-Croche plutonic Complex (Schrijver, in preparation) strongly suggest that major rotations of areal significance (block movements) did not occur subsequent to emplacement of these bodies.

Whether or not the sequence of events outlined above corresponds to reality clearly depends for a great deal on the regional water budget during metamorphism and thus on imponderables such as the rate of

[2] The author thus interprets migmatites as products of partial melting, a fashionable concept but rarely convincingly demonstrated from field relations (compare King, 1965).

diffusion of aqueous solutions at elevated temperatures and pressures—in a heterogeneous body of *deforming* rock. Nevertheless, pending more definitive knowledge of the behavior of rubidium and strontium isotopes under conditions of high-grade metamorphism and migmatization, geochronological tests of parts of this hypothesis seem possible.

DISCUSSION

The hypothesis discussed thus far admits of two entirely different interpretations:

1. The late, high-grade synkinematic metamorphism could be an entirely independent, temporally distinct event (compare Wynne-Edwards, 1969).

2. Both early and late metamorphic events are parts of one uninterrupted period of metamorphism, the early event corresponding to prograde metamorphism, and the late event corresponding to retrograde synkinematic metamorphism.

In areas where either or both (1) cover and basement are deformed and metamorphosed together but can be recognized, and (2) twice-deformed and once-deformed markers such as diabase dikes are present (compare Sutton and Watson, 1950), the former two-stage sequence of events could apply. On the other hand, where an intervening period of cooling, uplift, and unloading is not indicated, the latter one-stage sequence could apply.

In the area under consideration, basement and cover have not been recognized (see, however, Wynne-Edwards, 1969), and no evidence has been uncovered to support the postulate of a period of uplift or cooling intervening between an early and a late episode of high-grade metamorphism. Therefore, the author prefers the one-stage sequence of events consisting of (1) *early prograde metamorphism culminating in P-T conditions of the granulite facies and partial melting, followed uninterruptedly by* (2) *late, pervasive paracrystalline deformation during incipient retrograde metamorphism.*

Clearly, if this choice is correct, it is difficult if not impossible to reconstruct the position of the orthopyroxene isograd at the culmination of metamorphism. If, in fact, the orthopyroxene zone was more extensive than it is at present, the orthopyroxene isograd shown on the map (fig. 1) would be more correctly defined as indicating the *disappearance* of orthopyroxene from, rather than the "*first appearance*" of orthopyroxene in, quartz-bearing leucocratic rocks.

It remains to be answered which "event" in a protracted uninterrupted evolution as postulated here can be distinguished by geochronological methods.

THE ROLE OF THE MORIN ANORTHOSITE

As noted in the Introduction, the outstanding feature of the regional map pattern north and northwest of Montreal is that the orthopyroxene isograd and Wynne-Edwards' "composite isograd" partly enclose an orthopyroxene-grade terrane centered on the plutonites. Thus one other parameter is added to the set of spatially correlated properties across the orthopyroxene isograd: distance from the Morin Anorthosite. Although far less is known about the changes across the "composite isograd", Wynne-Edwards (1969, p. 171) has interpreted this regional map pattern as indicating contact metamorphism of the protoliths of the granulites by the plutonic anorthosite-mangerite complex prior to regional metamorphism associated with the "Grenville orogeny".

The association of anorthositic plutonic complexes with orthopyroxene-grade terranes seems even closer if the regional map pattern around the *Adirondack Anorthosite* is taken into account. In the State of New York, 150 km south of the area under consideration, Engel and Engel (1962, pl. 1) and de Waard (1967) show an orthopyroxene isograd at a minimum horizontal distance of 60 km west of the northwestern boundary of the Adirondack Anorthosite. The authors ascribe the isograd to the *first appearance* of orthopyroxene in amphibolites (Engel and Engel, 1962) and in quartz-bearing rocks (de Waard, 1967). In any case, the Adirondack plutonic complex, like the Morin plutonic complex, is surrounded by an orthopyroxene-grade terrane (disregarding the superimposed garnet-clinopyroxene isograd; see Martignole and Schrijver, 1971).

From the description by Engel and Engel (1962, p. 39), it appears that the changes across the isograd in the Adirondacks are different from those described in this paper. Toward the orthopyroxene zone they find "an increase in the amount of igneous-looking granite" (postkinematic migmatites?) and "an appreciable *increase*[3] in grain size of minerals". However, these statements are based on work carried out predominantly in a zone similar to what has been called the hornblende zone in this paper, whereas de Waard only discusses the higher-grade zone. Of course, it is possible that the differences between the Adirondack and Morin areas are real. It is equally possible that the relations west of the Adirondack Anorthosite are similar to those west of the Morin Anorthosite.

Unfortunately, we do not have similarly detailed data on the grade of metamorphism around other similar plutonic complexes in the Grenville province. It is known that some anorthosite masses—not necessarily similar to the Morin Anorthosite—are surrounded by rocks in the amphibolite facies (for example, Chown and Laurin, 1970). Furthermore, at least some orthopyroxene isograds do not conform to the present surface distribution of anorthosite masses (for example, de Waard, 1971, fig. 1). It seems that we must remain skeptical, for the moment, regarding extrapolations from local, perhaps spurious, correlations between the presence of anorthositic plutonic complexes and orthopyroxene-grade terranes. There are simply too many possibilities available to "explain" local relations. Last but not least, workers in granulite-facies terranes elsewhere would undoubtedly protest, with good reason, against too strict a cause-and-effect relation between anorthosite emplacement on the one

[3] Italics by K. Schrijver.

hand, and mineralogy, structure, and texture of "their" granulite-facies rocks on the other.

In conclusion, the author considers it unlikely that the association of the orthopyroxene zone with the Morin Anorthosite is due to contact metamorphism by the anorthosite mass. A less direct but more fundamental cause of the association of anorthositic plutonic masses and high-grade metamorphic terranes is to be sought in ductility- and density differences between intrusive masses and intruded rocks as outlined by Martignole and Schrijver (1970b, 1972).

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