# *The origin of three garnet isograds in Adirondack gneisses*

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*Summary.* Three isograds may be drawn, indicating increasing grades of metamorphism in the northern Adirondack area, based on the development of garnet successively in biotite-quartz–plagioclase paragneiss, metadolerite and metagabbro gneiss, and in syenite and quartz syenite orthogneisses. Changes in the accompanying minerals show that this is an order of increasing temperature. Rocks of similar chemical composition, suitable for the development of garnet, occur in each grade of metamorphism and geologic studies indicate adequate temperature and depth for the development of garnet even where it is not present. The degree of development of garnet in rocks of similar chemical composition, in even as high a grade as the pyroxene–granulite subfacies, is widely variable. All of the data are consistent with an hypothesis that the successive development of a garnetiferous facies for each of the different kinds of gneisses mentioned required special conditions that facilitated the kinetics of the reaction, such as temperature in excess of that for equilibria, in order for the garnet reaction to proceed. The data are not conclusive as to whether certain non-garnetiferous facies of amphibolites are due to the physical conditions (such as high partial pressure of $H_2O$ for the prevailing temperature and load pressure) or to non-equilibria.

## *Introduction*

A SERIES of Precambrian gneisses in the Adirondack area of New York state, U.S.A., have been formed under high-grade metamorphic conditions ranging from those of the sillimanite–almandine–muscovite subfacies to pyroxene–granulite subfacies as defined by Turner and Verhoogen (1960). It has been established (Buddington, 1952; Bartholemé, 1960) that all the garnets are of metamorphic origin.

Descriptions of other regions of progressive metamorphism report that garnet may occur systematically in mafic rocks, at as low a grade of metamorphism as that of the staurolite subfacies and locally even in the quartz–albite–epidote subfacies of the greenschist facies, and in pelitic rocks systematically at as low a grade as that of the garnet subfacies.

Yet in the Adirondack area garnet does not occur systematically in biotite-quartz-plagioclase paragneiss until the almandine–sillimanite–orthoclase subfacies of the amphibolite facies has been attained and not in amphibolite rocks until the upper range of the hornblende–granulite facies has been reached. The following discussion will deal with this problem.

*Regional development of garnet in Adirondack area*

There is a successive development of garnet in biotite–quartz–plagioclase paragneiss, metagabbro, and syenite-quartz syenite gneisses from the north-west to the south-east so that three isograds may be drawn (fig. 1). Also from the north-west to the south-east and east there are the following changes: muscovite and green biotite go to brown biotite and garnet in the paragneiss; K feldspar of syenitic-quartz syenitic gneisses from microcline through a variety that is clear in part and with a grid structure in part, to perthitic orthoclase; a change from amphibolites with blue-green hornblende and sphene through amphibolites with green or brownish green hornblende plus orthopyroxene, clinopyroxene, and ilmenite to granulitic mafic gneisses with garnet, orthopyroxene, and clinopyroxene; and an increase in the per cent. of $TiO_2$ in magnetite from less than 1 % in gneisses on the north-west to about 4 % on the south-east. The changes in minerals and mineral assemblages indicate increasing grade of metamorphic subfacies from that of the sillimanite–almandine–muscovite in the Emeryville area through a non-garnetiferous hornblende–granulite subfacies near Colton and a garnetiferous hornblende–granulite subfacies in a belt through Wanakena to the pyroxene–granulite subfacies east of isograd 3. The mineral assemblages indicate an increase of temperature from about 500–525° C on the north-west to 650° C or higher on the south-east. It is possible that pressure also increases concomitantly. Garnet does occur, but rarely, in amphibolites of the amphibolite subfacies in the zone of essentially non-garnetiferous rocks of the hornblende–granulite subfacies.

*Composition as a controlling factor in the development of garnet*

A number of examples are described in world literature where close association of garnetiferous and non-garnetiferous mafic rocks has been attributed by the author to variations in chemical composition. The *order of development* of garnet in different kinds of rock with increasing temperature (and pressure) in the Adirondacks is obviously controlled, in part, by composition. But, with certain exceptions, the development of garnet within a *particular* major kind of rock does not appear to be controlled in the Adirondack area by subordinate variations in its composition.

*Mafic and gabbroic anorthositic gneisses.* Anorthite, hypersthene, and olivine are the major reactants to yield garnet in the Adirondack mafic

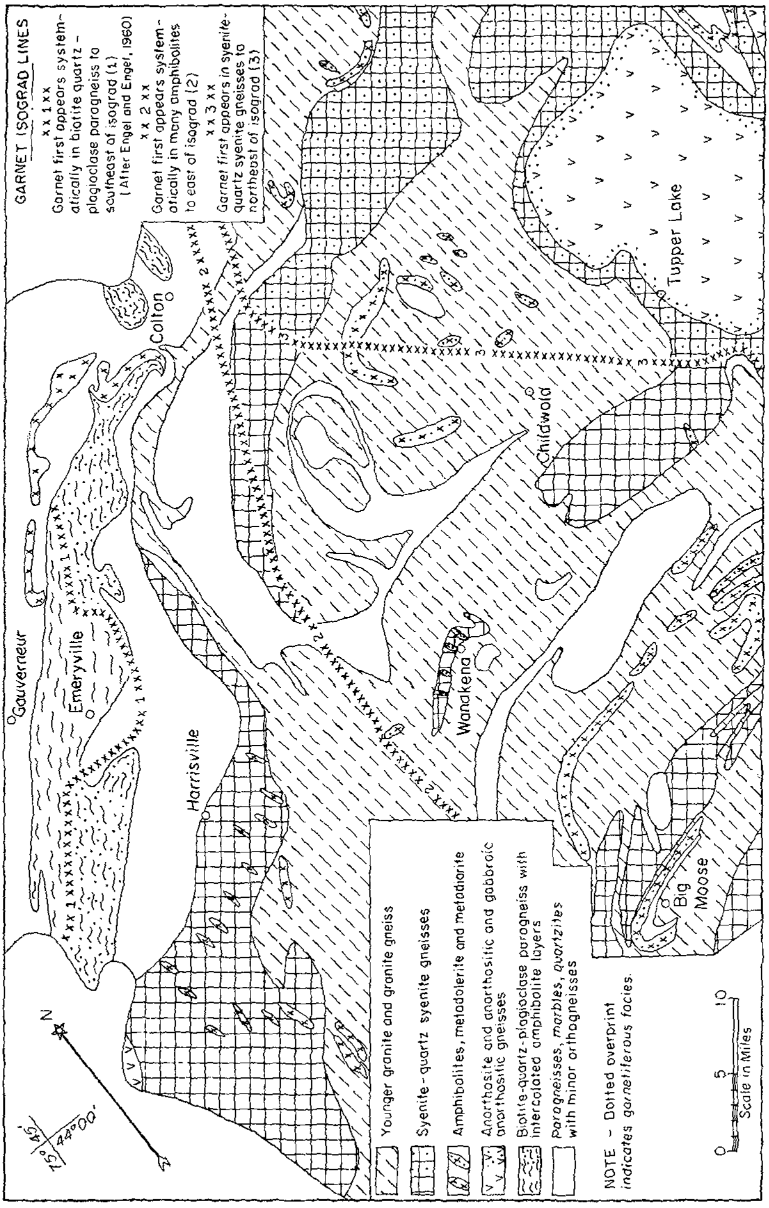


FIG. 1. Generalized geologic map of part of north-western Adirondacks, New York, showing three garnet isograds. The position of isograds in area of Younger granite and granite gneiss is based on mineralogy of included relics of older country rock.

rocks. The following equation represents the general type of reaction although variants are necessary for each specific rock. The plagioclase becomes more sodic:

$$\underset{\text{(Anorthite)}}{CaAl_2Si_2O_8} + \underset{\text{(Hypersthene)}}{2(Fe,Mg)SiO_3} + \underset{\text{(Olivine)}}{(Fe,Mg)_2SiO_4}$$

$$= \underset{\text{(Garnet)}}{(Fe,Mg)_3Al_2Si_3O_{12}} + \underset{\text{(Clinopyroxene)}}{Ca(Fe,Mg)Si_2O_6}$$

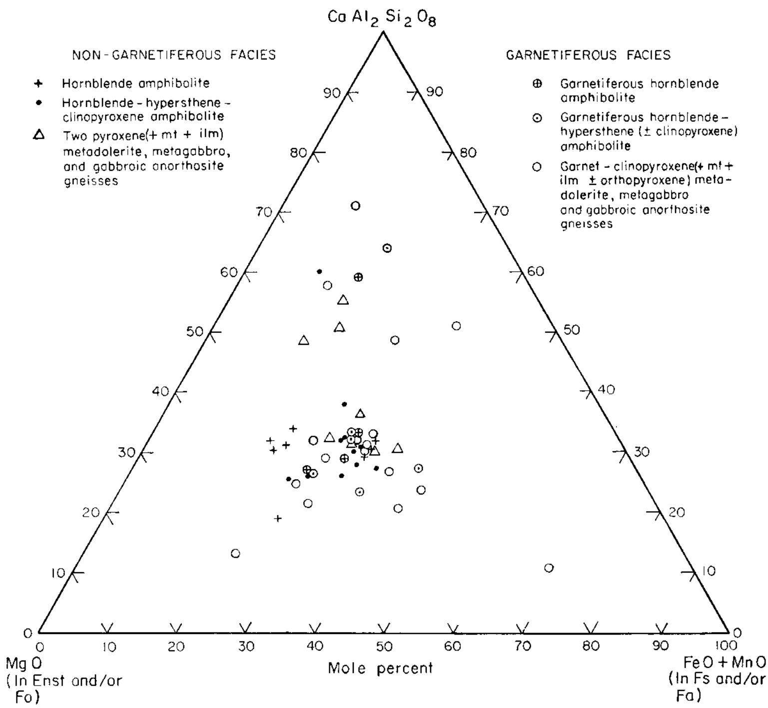


FIG. 2. Mole per cent. of normative $CaAl_2Si_2O_8$, MgO (of enstatite and/or forsterite), and FeO+MnO (of ferrosilite and/or fayalite) of metadolerites, metagabbros, amphibolites, and metagabbroic-anorthositic rocks.

Clinopyroxene is the predominant or exclusive mafic mineral (in absence of hornblende) where garnet forms as much as 20 wt. % of the rock. In hornblende-rich rocks $Ca(Fe,Mg)Si_2O_6$ is largely in the hornblende. The ratios for normative $CaAl_2Si_2O_8$, MgO (in normative enstatite and/or forsterite) and FeO (in normative ferrosilite and/or fayalite) are plotted in fig. 2. There are, of course, some subordinate reactions and interchange of material other than that of the major reactants. There is, however, extremely little, if any, reaction of magnetite or ilmenite to form garnet, for their per cent. in the mode of the garnet-rich pyroxene–plagioclase gneisses is about the same as for the norm. If the $p_{O_2}$ is low, however, presumably the $Fe_2O_3$ of magnetite would be reduced to FeO and react to yield garnet at appropriate $T$ and $P$. Data for all pertinent analysed metadoleritic, metagabbroic, amphibolitic, and gabbroic anorthositic rocks have been plotted. There is so great an overlap for the garnetiferous and non-garnetiferous rocks that no basis is evident for ascribing the development of garnet to a variation in the ratios of these three major constituents. There is a similar overlap if the norms for anorthite, hypersthene, and olivine are plotted on a ternary diagram.

Non-garnetiferous amphibolites occur as intercalated layers in biotite-quartz-plagioclase paragneiss of the Emeryville–Colton belt where they have been intensively studied by Engel and Engel (1962). In general these amphibolites have a different chemical composition from the garnetiferous mafic rocks in the core of the Adirondacks to the east. Engel and Engel (1962, p. 54) plotted CaO, $Al_2O_3$, and total iron as $Fe_2O_3$ on a ternary diagram and found that the non-garnetiferous amphibolites consistently have a lower $Al_2O_3$ ratio than the garnetiferous facies. They suggest therefore that composition may be the critical control in the development of the garnet rather than temperature or pressure. A lower ratio of $Al_2O_3/CaO$ results in a higher ratio of normative Ca(Mg,Fe) $Si_2O_6$ to normative hypersthene and/or olivine. A plot for mole per cent. anorthite, MgO+FeO (of hypersthene and/or olivine) and $Ca(Mg,Fe)Si_2O_6$ is given in fig. 3 to show the effect of a high ratio of clinopyroxene. Seven rocks with a ratio of $Ca(Mg,Fe)Si_2O_6$ higher than 30 % come from the zone of the pyroxene–granulite subfacies. Six of these have no garnet and the seventh only a few tenths of a per cent. Clinopyroxene has not entered into a reaction to form garnet, and thus where the $Al_2O_3/CaO$ ratio is so low that clinopyroxene is almost the exclusive mafic mineral there will be little or no garnet. The $Al_2O_3/CaO$ ratio, while critical to the extent indicated, is however only one of the factors controlling the development of garnets.

Two Adirondack examples are known where there are local garnetiferous facies of otherwise non-garnetiferous amphibolite. These are relatively rich in ferrous iron and this peculiarity of composition may have facilitated the development of garnet. (Cf. Wiseman, 1934.)

*Quartz-bearing syenite and quartz syenite orthogneisses.* Several non-garnetiferous syenite-quartz syenite orthogneisses, varying from mafic-rich to quartz-rich, and occurring within the lower temperature zones, have their garnetiferous counterparts of closely similar chemical composition in the highest temperature zone. This is consistent with a temperature control. Certain recrystallized shear zones within the

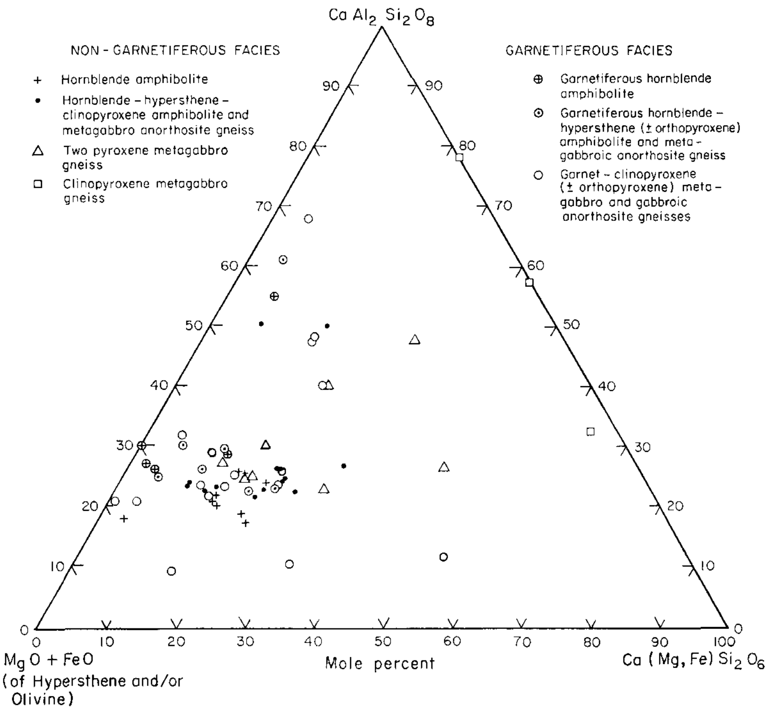


FIG. 3. Mole per cent. of normative $CaAl_2Si_2O_8$,$MgO+FeO$ (of hypersthene and/or olivine), and $Ca(Mg,Fe)Si_2O_6$ of metadolerites, metagabbro, amphibolites, and metagabbroic-anorthositic rocks.

orthogneisses of *all* of the temperature zones are garnetiferous in contrast to absence of garnet in the host gneiss (Buddington, 1963, p. 1176–1177), though both seams and host gneiss are of closely similar chemical composition. This indicates the development of garnet as a consequence of the catalytic effect of shearing or of localized higher temperature and pressure. An ACF plot shows overlap in composition of garnetiferous and non-garnetiferous facies. No general correlation between development of garnet and high ratio of FeO was found. Rocks with the mafic minerals (1) clinopyroxene + orthopyroxene, (2) clinopyroxene + orthopyroxene + hornblende, (3) orthopyroxene + hornblende and (4) hornblende, each assemblage with or without coexisting garnet, occur in the highest temperature zone: in this zone only rocks with substantial hornblende are in general non-garnetiferous, indicating $p_{H_2O}$ to be a factor. Some non-equilibria is also suspected.

*Biotite-quartz-plagioclase paragneisses.* Engel and Engel (1958, 1960) have thoroughly discussed the development of garnet in the biotite-quartz-plagioclase paragneisses and the following statements are based on their studies. Within the paragneiss of the sillimanite–almandine–muscovite subfacies garnet occurs only in or immediately associated with granite pegmatite veinings and is a variety with 5–7 wt. % MnO as contrasted with garnet of regional occurrence in the belts of paragneiss near Colton which has 0·5–0·7 % MnO. The present writer finds no significant differences in chemical composition of the paragneiss to explain the absence of garnet in the non-garnetiferous facies. The regional development of garnet is accompanied by a decrease in the amount of biotite and quartz in the garnetiferous facies.

### *Role of partial pressure of* $H_2O$

The concept that non-garnetiferous or garnetiferous amphibolites may form from rocks of similar composition at similar $T$ and depth but different partial pressure of $H_2O$ has been applied by Wilcox and Poldervaart (1958) to a swarm of metadolerite dikes in North Carolina.

It has also been demonstrated by Wilcox and Poldervaart (1958) and by Gjelsvik (1952) that reconstitutions to non-garnetiferous amphibolites need not necessarily be accompanied by change in chemical composition.

Evidence is presented elsewhere (Buddington, 1963) that in the Adirondacks both garnetiferous and non-garnetiferous amphibolites as well as rocks of the pyroxene–granulite subfacies, where associated together, were all developed under similar temperature and load pressure but the hornblendic rocks under a higher partial pressure of $H_2O$.

The No. 2 isograd (fig. 1) lies *within* the zone of the hornblende–granulite subfacies, with non-garnetiferous amphibolites on one side and garnetiferous amphibolites on the other. The isograd is primarily the consequence of an increase of temperature but the effect of the temperature may be interpreted either as that requisite for the development of garnet as a member of an equilibrium assemblage *or* as that necessary

TABLE I. Chemical analyses of garnet-poor (or non-garnetiferous) and garnet-rich rocks of similar chemical composition and similar grade of metamorphism

Three grades of metamorphism are represented

| | 1 (4930) | 1-a (885) | 2 (5980-a) | 2-a (5483) | 3 (906) | 3-a (899) | 4 | 4-a | 5 | 5-a |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 49·15 | 50·00 | 47·99 | 46·25 | 49·17 | 47·38 | 42·45 | 39·61 | 50·35 | 52·60 |
| $TiO_2$ | 1·76 | 1·94 | 0·93 | 1·83 | 3·05 | 3·67 | 4·24 | 4·42 | 0·31 | 0·39 |
| $Al_2O_3$ | 16·12 | 16·01 | 16·90 | 17·51 | 13·63 | 13·15 | 13·27 | 12·09 | 24·09 | 23·66 |
| $Fe_2O_3$ | 2·35 | 1·86 | 1·49 | 1·81 | 3·90 | 4·46 | 6·03 | 7·22 | 1·11 | 0·91 |
| FeO | 9·85 | 11·13 | 9·69 | 10·20 | 11·20 | 11·67 | 15·02 | 15·45 | 4·54 | 3·91 |
| MnO | 0·17 | 0·18 | 0·14 | 0·18 | 0·18 | 0·18 | 0·26 | 0·30 | 0·06 | 0·06 |
| MgO | 6·21 | 5·92 | 9·56 | 9·34 | 4·15 | 5·33 | 5·97 | 7·30 | 4·22 | 3·17 |
| CaO | 8·55 | 8·56 | 8·99 | 8·69 | 8·21 | 8·48 | 10·24 | 11·98 | 10·81 | 10·45 |
| $Na_2O$ | 2·81 | 2·89 | 2·85 | 2·48 | 3·14 | 3·00 | 1·39 | 0·56 | 3·52 | 3·61 |
| $K_2O$ | 1·15 | 0·98 | 0·76 | 0·55 | 1·14 | 1·06 | 0·28 | 0·20 | 0·44 | 0·67 |
| $H_2O+$ | 0·49 | n.d. | 0·39 | 0·67 | 1·04 | 0·69 | 0·26 | 0·34 | 0·28 | 0·22 |
| $H_2O-$ | 0·02 | n.d. | 0·06 | 0·10 | 0·23 | 0·33 | 0·21 | 0·18 | 0·09 | 0·10 |
| $P_2O_5$ | 0·20 | 0·25 | tr. | 0·28 | 0·52 | 0·59 | 0·15 | 0·40 | 0·02 | 0·03 |
| $CO_2$ | 1·28 | tr. | | 0·09 | 0·28 | 0·04 | 0·00 | 0·02 | 0·04 | 0·02 |
| S | | 0·05 | | | 0·09 | 0·10 | | | | |
| Total | 100·11 | | 99·75 | 99·98 | 99·93 | 100·13 | 99·77 | 100·07 | 99·88 | 99·80 |

Approximate modes, wt. %

| | 1 | 1-a | 2 | 2-a | 3 | 3-a | 4 | 4-a | 5 | 5-a |
|---|---|---|---|---|---|---|---|---|---|---|
| Plagioclase | 50·9 | 45·6 | 54·4 | 31·9 | 50·2 | 47·8 | 40·5 | 15·1 | 79·9 | 73·4 |
| K feldspar | 1·2 | — | — | — | 0·5 | — | — | — | 8·0 | 0·3 |
| Orthopyroxene | 27·0 | 43·7 | 19·1 | 16·4 | 20·7 | 3·7 | 15·5 | 5·0 | — | 5·8 |
| Clinopyroxene | 13·5 | | 4·7 | — | 19·4 | 23·7 | 23·9 | 41·8 | 3·6 | |
| Hornblende | — | 4·9 | 10·3 | 41·9 | — | — | 6·5 | 4·8 | 4·4 | 16·8 |
| Biotite | 1·7 | 0·9 | 1·9 | 0·6 | — | 2·8 | — | — | 3·4 | 0·1 |
| Garnet | — | 2·4 | — | 6·7 | 0·6 | 16·0 | 2·6 | 21·4 | 0·4 | 3·5 |
| Opaques | 5·2 | 2·0 | 1·1 | 1·8 | 7·6 | 5·3 | 9·6 | 11·4 | 0·2 | 0·2 |
| Quartz | — | — | — | — | — | 0·3 | 0·8 | — | — | — |
| Olivine | — | — | 8·0 | — | — | — | — | — | — | — |
| Apatite | 0·5 | 0·5 | | 0·7 | 1·0 | 0·4 | — | — | — | — |

to afford the rate of reaction for the development of garnet under conditions where it was already a potentially stable mineral. The evidence is not clear as to whether the non-garnetiferous amphibolites, in general, formed as stable equilibria assemblages under a relatively high partial pressure of $H_2O$ or as unstable assemblages. Garnet does occur, though rarely and apparently sporadically in the zones of predominantly non-garnetiferous amphibolites.

### *Depth (load pressure) as a controlling factor in the development of garnets in mafic rocks*

Ever since Fermor (1913), many petrologists have emphasized pressure (cf. Miyashiro, 1958, pp. 265–271; Shido, 1958, pp. 209–212) as a major factor in controlling the development of garnet. The effective absence of garnet from the Adirondack rocks of the amphibolite facies and lower hornblende–granulite subfacies would on this hypothesis be attributed to a relatively shallow depth of development. This is not consistent with other data. Andalusite (generally inferred to be a development of high temperature and relatively shallow depth) has never been reported in the Adirondacks; sillimanite is its equivalent. The development of granoblastic orthogneisses from dolerite, gabbro, syenite, quartz syenite, and granite has been so extensive and intensive that

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Legend to Table I

Zone of predominant sillimanite-almandine-orthoclase subfacies.

1 (4930). Metadolerite gneiss, dyke in quartz-syenite gneiss. 4·5 miles south-west of Harrisville, N.Y. (Buddington, 1939, p. 134).

1–a (885). Metadolerite gneiss (fine grain), dyke in pyroxene syenite gneiss. 6·4 miles south-south-east of Natural Bridge, N.Y. Exceptionally fine grained and the *only* dyke with garnet in this metamorphic zone. Analyst, Yozo Chiba.

Zone of predominant hornblende–granulite subfacies.

2 (5980-a). Olivine metadolerite, about 10 miles south of Harrisville, N.Y. (Buddington, 1939, p. 60).

2-a (5483). Garnet–hornblende–hypersthene amphibolite, 2·5 miles east-south-east of St. Regis Falls, N.Y. (Buddington, 1939, p. 60).

Zone of predominant pyroxene-granulite subfacies.

3 (906). Metadolerite gneiss, dyke in gabbroic anorthosite gneiss. 1·2 miles east-south-east of Keeseville, N.Y. Analyst, Yozo Chiba.

3-a (899). Metadolerite gneiss, dyke in gabbroic anorthosite gneiss. 1·75 miles south-east of Port Kent, N.Y. Analyst, Yozo Chiba.

4 Mafic gneiss, basal part of sheet of gabbroic anorthosite gneiss. Speculator Mtn., N.Y. (Bartholomé, 1956).

4-a. Garnetiferous mafic gneiss. Same locality and reference as no. 4.

5. Gabbroic anorthosite gneiss, Speculator Mtn., N.Y. (Bartholomé, 1956).

5-a. Garnetiferous gabbroic anorthosite gneiss, same locality and reference as no. 5.

probability would favour deformation at great depths. Engel and Engel (1962, p. 39) estimated a depth of burial of at least 5 to 7 miles and perhaps as great as 10 to 15 miles, based on stratigraphic and structural reconstructions for the Emeryville–Colton belt of metamorphism. Thus the lack of development of garnet in rocks of the amphibolite and non-garnetiferous hornblende–granulite subfacies of the Adirondacks does not appear to be consistent with development at relatively low pressures. Pressure has been adequate for garnet.

*Excess temperature, a requirement for the regional garnet reaction in the Adirondack area*

If we assume that garnet may be a mineral of a stable assemblage in metamorphic rocks of suitable composition formed at as low grades of metamorphism as that of the sillimanite–almandine–muscovite subfacies then the preceding discussion has presented evidence that temperature, pressure, composition, and partial pressure of $H_2O$ were all appropriate for the development of garnet in certain rocks of large Adirondack areas where it is actually absent. Yoder (1952, pp. 621–622) has proposed that the chlorite, biotite, and garnet isograds in metasedimentary rocks are 'dependent on the attainment of a sufficient reaction rate such that a mineral will appear'. The possibility that the successive appearance of garnet in different kinds of rock in the Adirondacks is dependent upon a temperature adequate to promote the rate of reaction necessary for its development and in excess of that requisite for stability will be considered next.

The terms capricious, irregular, occasional, erratic, local, isolated, trace, rare, variable, and sporadic have been used by petrologists to describe the apparently unsystematic development of garnet in certain metamorphic zones of many regions. This kind of distribution, of course, suggests non-equilibria as one possible explanation.

The unequal development of garnet in rocks approximating the same chemical composition from the same outcrop or from outcrops in the same zone of metamorphism is widespread in the Adirondacks. Chemical and mineralogical data for 5 pairs of rocks with similar chemical composition and belonging to 3 different grades of metamorphism are given in table I. One of each of the 5 pairs of rocks has little or no garnet in contrast to the other that has substantial garnet. The extensive occurrence of non-equilibria in the rocks of such high grades of metamorphism lends weight to the hypothesis that the successive development of garnet in the different kinds of rock concomitant with rise of temperature and pressure may require an excess of temperature above that for equilibria to effect reaction.

Non-equilibrium is further demonstrated by the occurrence of beds of non-garnetiferous biotite–quartz–plagioclase paragneiss within the zone of the hornblende–granulite subfacies.

## *Conclusions*

The temperatures required to form garnet vary with the minerals entering into the chemical reactions. In quartz-bearing charnockitic gneisses, biotite may be expected to react at lower temperatures than hypersthene to yield garnet. Hypersthene may thus occur without clinopyroxene in coexistence with garnet as in the type area near Madras, India. Evidence has been presented that emphasizes non-equilibrium as a factor in garnet formation. There is a need to evaluate such possibilities as that in chemically similar mafic rocks garnet may develop at moderate temperature in a greenschist mineral assemblage but requires excess temperature to form from a basaltic or gabbroic assemblage.

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## *References*

Bartholomé (P.), 1956. Princeton Ph.D. thesis.
—— 1960. Econ. Geol., vol. 55, p. 255.
Buddington (A. F.), 1939. Geol. Soc. Amer., Mem. 7.
—— 1952. Amer. Jour. Sci., Bowen vol., p. 37.
—— 1963. Bull. Geol. Soc. Amer., vol. 74, p. 1155.
Engel (A. E. J.) and Engel (C. G.), 1958. Bull. Geol. Soc. Amer., vol. 69, p. 1369.
—— 1960. *Ibid.*, vol. 71, p. 1.
—— 1962. Geol. Soc. Amer., Buddington vol., p. 37.
Fermor (L. L.), 1913. Records Geol. Survey India, vol. 43, pt. 1, p. 41.
Gjelsvik (T.), 1952. Norsk Geol. Tidsskrift, vol. 30, p. 33.
Miyashiro (A.), 1958. Journ. Fac. of Sci., Univ. of Tokyo, Ser. II, vol. 11, p. 219.
Shido (F.) 1958. *Ibid.*, p. 131.
Turner (F. J.) and Verhoogen (J.), 1960. Igneous and Metamorphic Petrology, McGraw-Hill.
Wilcox (R. E.) and Poldervaart (A.), 1958. Bull. Geol. Soc. Amer vol. 69, p. 1323.
Wiseman (J. D. H.), 1934. Quart. Journ. Geol. Soc., vol. 90, p. 354.
Yoder (H. S.), 1952. Amer. Journ. Sci., Bowen vol., p. 569.