

Garnets as indices of progressive regional metamorphism

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Summary. Garnets undergo readjustment of ion-assemblages under external mechanical and thermal stresses; this adjustment favours those paths that annul the very cause to which it is due. Metal ions in garnets being replaceable, with rising metamorphism garnets become reluctant to accommodate ions of larger ionic radii.

Data from recent literature on chemical analyses of garnets from rocks belonging to different grades of regional metamorphism reveal that the (FeO+MgO) content of garnet varies linearly with (CaO+MnO) content. As the Fe/Mg ratio does not vary appreciably, a fair estimate of metamorphic grade can be made from a knowledge of (CaO+MnO) or of (FeO+MgO) individually or even, with less confidence, of FeO or MgO alone. From the study of the available data it is found that (CaO+MnO) and (FeO+MgO)/(CaO+MnO) provide the best indicators of progressive metamorphism. Cell edges of garnets decrease progressively with increasing metamorphism and this may also be used as a fairly good index of metamorphism. When cell edges are plotted against (FeO+MgO)/(CaO+MnO), a hyperbolic curve is obtained.

THE index minerals chlorite, biotite, almandine garnet, kyanite, staurolite, and sillimanite have long been used for the determination of the grade of regional metamorphism in rocks of pelitic composition. Recently it has been shown that an individual mineral or a pair of diadochic minerals change progressively in composition with rising metamorphism (Engel and Engel, 1958); use of this principle permits more minute demarcation of the intensity of regional metamorphism.

Miyashiro (1953) also found significant correlation between grade of metamorphism and the MnO, CaO, and FeO content (wt. %) of Ca-poor garnets. The variation in MnO shown by him agrees well with that obtained by Barth (1936).

Sturt (1962) has confirmed graphically the continuous variation of (FeO+MgO) and (CaO+MnO) with metamorphic grade in a diagram in which he plotted (FeO+MgO) content of garnets against (CaO+MnO) content of garnets from pelitic rocks of varying metamorphic grades. Further he was able to correlate the variation of CaO in garnet with the ratio (Cell edge/Refractive index). These results were obtained

on samples from a limited range of localities. It remains to be verified how far Sturt's results are valid for other areas.

A quantitative approach to the problem of metamorphic grading

From a study of the available compositional and cell-edge data for garnets in regionally metamorphosed rocks, the author has noted

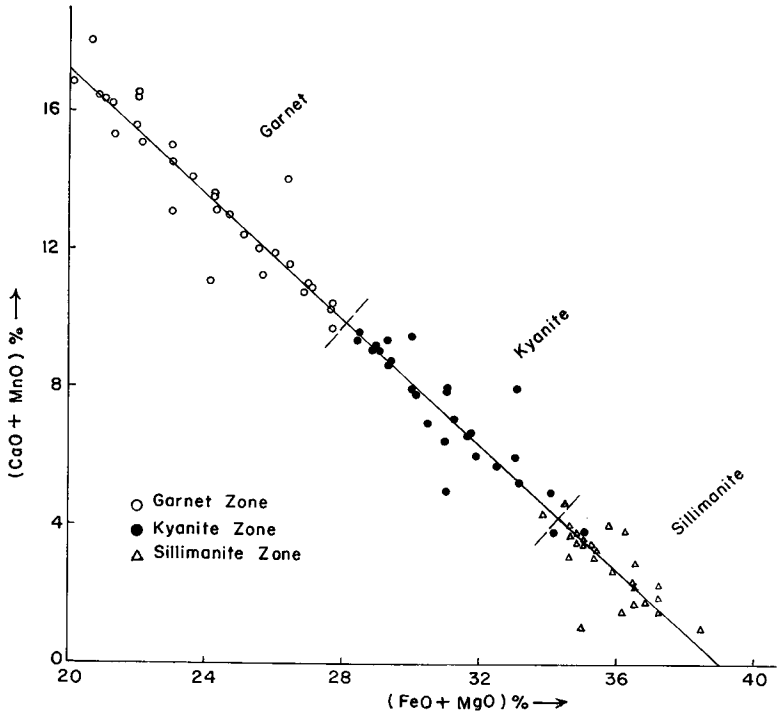


FIG. 1. Nature of variation of $(\text{FeO} + \text{MgO})$ with $(\text{CaO} + \text{MnO})$ in garnets with different grades of metamorphism.

certain systematic variations that appear to be of considerable importance in estimating grades of metamorphism of the garnet-bearing rocks. Data on physical and chemical analyses of 84 samples of garnets belonging to different grades of regionally metamorphosed pelitic rocks were compiled from current literature (Atherton, 1964; Kretz, 1964; Lee, Coleman, and Erd, 1963; Frost, 1962; Sturt, 1962; Miyashiro, 1953).

Garnets undergo readjustment of ion-assemblages under external mechanical and thermal stresses; this adjustment favours those paths

that annul the cause to which it is due. The ionic radii of Ca^{2+} , Mn^{2+} , Fe^{2+} , and Mg^{2+} are 0.99, 0.80, 0.74, and 0.66 Å respectively. According to Braun's principle of mobile equilibrium Ca^{2+} and Mn^{2+} ions can be afforded space in a system under relatively lower stress, but with increase in stress the system adjusts itself in such a way as to be relieved of the stress, and as a result the garnet system tends to become

TABLE I. Maximum numbers of samples overlapping between successive zones of metamorphism using several parameters individually

	Garnet/Kyanite boundary	Number of overlapping samples with higher or lower zone
$\text{FeO} + \text{MgO}$	28.1 %	0
$\text{CaO} + \text{MnO}$	9.9	1
FeO	25.0	3
$\text{FeO} + \text{MgO}$	4.0	2
$\text{CaO} + \text{MnO}$		
a^*	11.61 Å	2
	Kyanite/Sillimanite boundary	
$\text{FeO} + \text{MgO}$	34.3	3
$\text{CaO} + \text{MnO}$	4.2	3
FeO	32.0	8
$\text{FeO} + \text{MgO}$	13.5	0
$\text{CaO} + \text{MnO}$		
a^*	11.538 Å	0

* Cell edge data are available for 52 samples only.

richer in Fe^{2+} and Mg^{2+} with elimination of Ca^{2+} and Mn^{2+} ions. The trend of variation of total $(\text{CaO} + \text{MnO})$ vs. $(\text{FeO} + \text{MgO})$ (fig. 1) in garnets collected from the sillimanite, kyanite, and garnet zones of pelitic metamorphic rocks can thus be interpreted in the light of the principle of mobile equilibrium, and confirms Sturt's suggestion of linear variation in garnets with increasing metamorphism. The equation of the line in fig. 1 is $y = 39.5 - 1.012x$, and the correlation coefficient is -0.90 . The equation is computed on the basis of the 'reduced major axis' (Kermack and Haldane, 1950), which is in fact the geometric mean of the two regressions; as a method, though not ideal, it is in this instance acceptable because the slopes of both the regressions are not far from unity and the probable errors of the two variables are roughly the same.

The main implication of this empirical linear relation is that whatever

the changes in Ca : Mn ratio may be, there can be no great change in Fe : Mg ratio throughout the series and in the fig. 1 the Fe/(Fe+Mg) ratio increases slightly from 0.68 (the value corresponding to FeO+MgO = 39 % and CaO+MnO = 0 %) to about 0.72 to 0.76

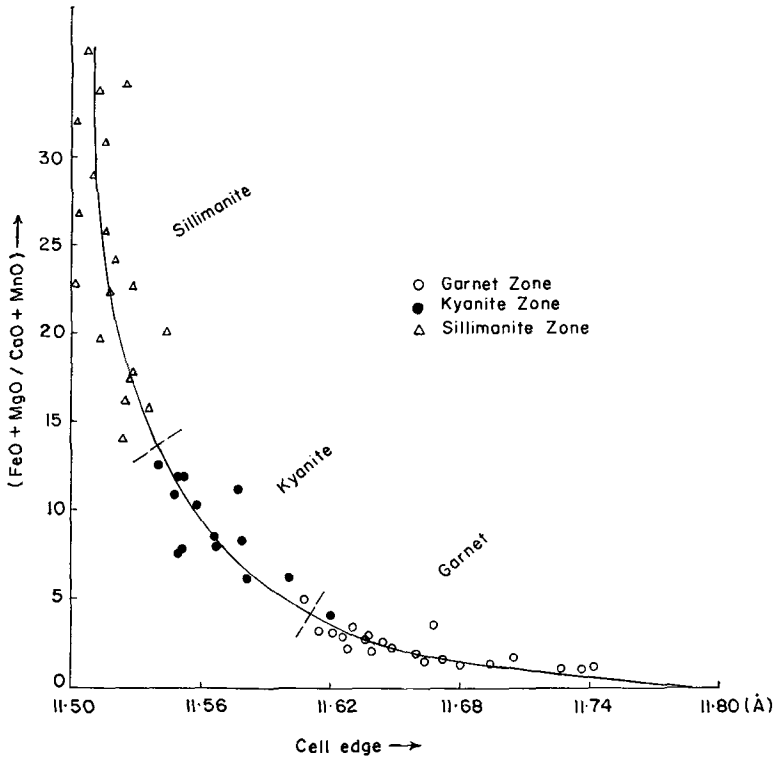


FIG. 2. Variation of the ratio $(\text{FeO} + \text{MgO}) / (\text{CaO} + \text{MnO})$ with cell edge (a) in garnets with varying grades of metamorphism. Here also well marked regions are observed.

depending on the Ca/Mn ratio at $\text{CaO} + \text{MnO} = 17\%$. These relations also follow from the percentage compositions of the garnet end members, calculated assuming the trivalent cations are wholly aluminium.

The consequences of the good linear correlation are that the Fe/Mg ratio cannot vary appreciably, also that a fair estimate of metamorphic grade can be made from a knowledge of $(\text{CaO} + \text{MnO})$ or of $(\text{FeO} + \text{MgO})$ individually or even, with less confidence, of FeO or MgO alone (since Fe/Mg varies little); it is not always essential to know all four.

Attempts were therefore made to test the suitability of several parameters as individual indicators of the grade of regional metamorphism of pelitic rocks. The following parameters were considered: $(\text{CaO} + \text{MnO})$, $(\text{FeO} + \text{MgO})$, FeO , the ratio $(\text{FeO} + \text{MgO})/(\text{CaO} + \text{MnO})$, and the cell-side, a . On the straight line of fig. 1, the garnets belonging to the Garnet zone are well separated from those in the Kyanite zone while only 3 samples appear to overlap between the boundaries of the Kyanite and Sillimanite zones. It is clear, therefore, that the position of a sample on this line is a good indicator of its degree of metamorphism.

The number of overlaps between successive zones may be considered as a good criterion for testing the effectiveness of particular parameters as indicators of the degree of metamorphism. The result of such an investigation will be revealed from table I. It appears that in general the distinction between Garnet and Kyanite zones may be made more effectively than in that between Kyanite and Sillimanite zones. On the whole, the number of overlaps is the least in the case of $(\text{FeO} + \text{MgO})/(\text{CaO} + \text{MnO})$ ratio, which thus appears to be the most effective in this respect. However, the cell side, a , and the $(\text{FeO} + \text{MgO})$ percentage are also fairly effective.

It is interesting to note that there is a good correlation between the grade of metamorphism of individual samples as indicated by the ratio $(\text{FeO} + \text{MgO})/(\text{CaO} + \text{MnO})$ and that by the cell edge a . This is well expressed by the hyperbolic relationship between these two parameters (fig. 2).

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