

An evaluation of garnet-clinopyroxene geothermometry in granulites*

Craig A. Johnson^{1**}, Steven R. Bohlen², and Eric J. Essene³

¹ Department of Geological Sciences, The University of Michigan, Ann Arbor, Michigan 48109, USA

² Department of Earth and Space Sciences, State University of New York, Stony Brook, New York 11794, USA

³ Department of Geological Sciences, The University of Michigan, Ann Arbor, Michigan 48109, USA

Abstract. Four new formulations of the garnet-clinopyroxene geothermometer (Ellis and Green 1979; Ganguly 1979; Saxena 1979; Dahl 1980) have been evaluated in the Adirondacks and five other granulite terranes using results from 94 mineral pairs. The Saxena and Ganguly formulations give temperatures that are generally 100–150° C above those constrained by phase equilibria and other independent thermometry while the empirical calibration of Dahl gives widely scattered, erratic results. Despite some scatter in the data, the Ellis and Green calibration appears to be more accurate and precise than the others and is the most useful garnet-clinopyroxene thermometer currently available for quantitative thermometry in granulites. All four formulations are sensitive to large variations (> 70–80° C) in temperature suggesting that problems with accuracy and precision can be improved with further refinement of model-based aspects of the thermometers.

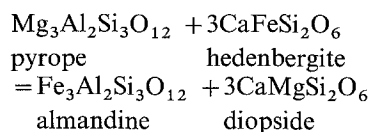
Introduction

Petrologists have long sought a widely applicable geothermometer. As a result, there has been substantial effort in developing thermometers that depend on the distribution of a pair of cations or groups of cations between coexisting phases, the so-called K_D ¹ thermometers. An attractive aspect of these thermometers is their apparent simplicity of application, requiring only an analysis of coexisting phases. K_D thermometers are, perhaps, the most widely applied and yet the most poorly calibrated thermometers. The effects of extensive substitutions on Mg–Fe distribution in such systems as biotite-garnet, hornblende-garnet and garnet-clinopyroxene have not been fully evaluated, and there has been little assessment of the accuracy and precision of these thermometers. For garnet-clinopyroxene (Mg–Fe) thermometry, several workers have recently begun to address the problems of Mg–Fe distribution as a function of vari-

able mineral composition in addition to P and T , and four new calibrations have been published (Ellis and Green 1979; Ganguly 1979; Saxena 1979; Dahl 1980). If properly calibrated, the garnet-clinopyroxene thermometer would be of great value since the assemblage is found in an array of rock types spanning a broad temperature range, from 300–400° C eclogites to albite-epidote amphibolites, amphibolites, granulites to 1,200° C garnet peridotite. This potential underscores the need to carefully evaluate the accuracy and precision of the thermometer.

Garnet-clinopyroxene geothermometry

The temperature dependence of Mg–Fe²⁺ exchange between garnet and clinopyroxene has long been recognized as a potential geothermometer. A number of workers (Banno and Matsui 1965; Coleman et al. 1965; Evans 1965a; Essene and Fyfe 1967; Lovering and White 1969; Banno 1970; Mysen and Heier 1972) noted the correlation between the distribution coefficient (K_D) for the exchange reaction:



and equilibration temperatures of different eclogite types. In a review of over 300 localities, Irving (1974) showed that $K_{D, \text{Fe-Mg}}^{\text{gt-cpx}}$ varies from greater than 25 for garnet-clinopyroxene pairs in blueschist terranes to nearly 1 in garnet peridotites, but noted that within a single terrane K_D could vary substantially as the probable result of mineral zoning (Evans 1965b; Essene and Fyfe 1967; Dudley 1969; Bryhni and Griffin 1971). Several studies have been conducted to evaluate the T dependence of K_D and to quantify the effects of pressure and bulk composition. Mysen and Heier (1972) proposed an empirical calibration for the garnet-clinopyroxene thermometer ($T(\text{K}) = 2475/(\ln K_D + 0.781)$) based on the estimated equilibration temperatures of a variety of eclogites. Mori and Green (1978) equilibrated several natural garnets and clinopyroxenes between 950–1,500° C and 30–40 Kbar and derived the T dependence of K_D ($T(\text{K}) = 2800/\ln K_D + 1.19$) for garnet lherzolite compositions. Raheim and Green (1974) experimentally calibrated K_D as a function of P and T for natural basaltic compositions crystallized in the eclogite field at 20–40 Kbar and temperatures

Offprint requests to: S.R. Bohlen

* Contribution No. 392 from the Mineralogical Laboratory, Department of Geological Sciences, The University of Michigan, Ann Arbor, MI. 48709, USA

** Present address: Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520, USA

1 K_D , the distribution coefficient, is defined as the ratio of cations in coexisting minerals. $K_{D, \text{Fe-Mg}}^{\text{gt-cpx}}$ is calculated as $(X_{\text{Fe}}^{\text{gt}}/X_{\text{Mg}}^{\text{gt}})/(X_{\text{Fe}}^{\text{cpx}}/X_{\text{Mg}}^{\text{cpx}})$

primarily in the range of 1,000–1,500° C ($T(K) = (3686 + 28.35P(Kb))/(\ln K_D + 2.33)$). They noted that K_D was not affected by whole rock Mg/Fe ratio (from $Mg/(Fe^{2+} + Mg) = 0.062 - 0.85$) but implied that K_D had a substantial dependence on bulk composition. Raheim and Green concluded that K_D was more sensitive to pressure than predicted from molar volume data (Banno 1970). Such a conclusion has stirred considerable debate and further work has shown that the magnitude of the pressure effect may itself be compositionally dependent (Wood 1975, 1976, 1977).

Additional studies have been conducted to evaluate the importance of various compositional parameters to K_D and to experimentally, empirically, or theoretically formulate garnet-cpx thermometers applicable over a wide range of $P-T-X$. Ellis and Green (1979) experimentally calibrated the effect of Ca on $K_{D, Fe-Mg}^{gt-cpx}$ as

$$T(K) = (3104X_{Ca}^{gt} + 3030 + 10.86P(Kb))/(\ln K_D + 1.9034)$$

and deduced a pressure dependence of less than half of that determined by Raheim and Green. Ganguly (1979) and Dahl (1980) have examined the effects of Mn in addition to other variables, Fe/Mg, Ca and pressure. Ganguly's formulation,

$$T(K) = (4801 + 11.07P(Kb) + 1586X_{Ca}^{gt} + 1308X_{Mn}^{gt})/(\ln K_D + 2.93),$$

is based on experimental and thermochemical data while Dahl's thermometer,

$$T(K) = (2482 + 1509(X_{Fe}^{gt} - X_{Mg}^{gt}) + 2810X_{Ca}^{gt} + 2855X_{Mn}^{gt})/R \ln K_D,$$

has been empirically derived from a granulite terrane in southwest Montana (Dahl 1979). Saxena (1979) has developed a thermometer for the system $Na_2O - MgO - FeO - MnO - Al_2O_3 - SiO_2$, formulated as $T(K) = (8288 + 27.6P(Kb) + Q1 - Q2)/(R \ln K_D + 2.4083)$, where Q1 and Q2 are functions of garnet and clinopyroxene compositions respectively, based on available experimental and thermochemical data. Estimated confidence levels for these thermometers are generally $\pm 5\%$ in the temperature range 800–1,200° C, although the authors note that errors may be somewhat larger toward the low temperature end of this range as a result of the lack of extensive experimental data or well constrained thermochemical parameters at such temperatures. The effect of significant jadeite solution and accompanying cation ordering for low-temperature eclogites has not yet been accommodated by present thermometers. The thermometers apply to low Na, Cr mineral compositions that encompass the vast majority of coexisting garnets and clinopyroxenes found in granulite terranes.

There are few rigorous, systematic evaluations of these thermometers. Bohlen and Essene (1980) applied Raheim and Green's thermometer to granulites in the Adirondacks. They found a significant dependence of $K_{D, Mg-Fe}^{gt-cpx}$ on Mg/Fe ratio and concluded that the thermometer was imprecise and not useful in distinguishing small variations (< 70–100° C) in metamorphic T. Carswell and Gibb (1980) tested the formulations of Raheim and Green, Mori and Green, Ellis and Green, Ganguly and Saxena in garnet lherzolites, and concluded that the Mori and Green and Ellis and Green thermometers give more reasonable temperatures than those of other workers.

Analytical procedures

Most analyses of coexisting garnet-clinopyroxene were taken from the literature. However, data from the literature was used only if: 1) elemental oxide totals for the mineral analyses were $100 \pm 1.5\%$ and the stoichiometries did not deviate by more than 2% in any cation site from ideal garnet or clinopyroxene mineral formulae, 2) authors had evaluated mineral homogeneity and analyses were obtained on locations within minerals that were broadly homogeneous (generally with variations of less than 2 mol% of major element endmembers), 3) analyses were obtained from garnet-clinopyroxene pairs in physical contact in rocks that showed no evidence of extensive retrograde metamorphic effects¹. The same selection criteria applied to our own data for Adirondack garnet-clinopyroxene pairs (Bohlen and Essene 1980; Johnson and Essene 1982). In order to evaluate garnet zoning, traverses of spot analyses were made on several Adirondack garnets in contact with clinopyroxene using the University of Michigan ARL-EMX electron microprobe equipped with LiF, PET, and TAP crystal spectrometers. At a given spot Fe, Mn, Mg, Si and Al were measured using wavelength dispersive techniques; Ca was analyzed using a Kevex Li-drifted silicon detector. The data were corrected for atomic number, absorption, fluorescence, background and machine drift using the computer program EMPADR VII (Rucklidge and Gasparini 1969). Counting times were approximately 60 seconds (15 Kv, 0.005–0.008 μ A sample current) to ensure that random errors associated with counting statistics are less than 1% for Fe and Mg and less than 2% for Mn and Ca. For all of the analyses used in this study, garnet and clinopyroxene formulae were normalized about 8 and 4 cations respectively, and ferric iron was inferred from stoichiometry.

Thermometry evaluation

Field areas used to properly evaluate any thermometer should ideally satisfy several criteria. Temperature should be well constrained by both phase equilibria and by other independent thermometers, and should show variation (preferably 100° C) across the terrane. Pressure should also be well constrained. The terrane should have a range of lithologies providing a wide variation in mineral compositions so that compositional dependencies of the thermometer being tested can be evaluated. A very restricted range of compositions may give false impressions of precision or accuracy of a given thermometer. In addition, the nature of the fluid phase, if any, should be well defined, even though the metamorphic fluid may have no direct effect on the thermometer. Finally, there should be no polymetamorphic, retrograde metamorphic, or other re-equilibration features present. Ideally the terrane should have equilibrated during a single thermal event with subsequent rapid cooling to quench in equilibrium composition.

In granulite terranes, these final considerations are difficult to evaluate. Investigations of Phanerozoic metamorphic terranes clearly show that regional metamorphism is a protracted event with more than one thermal-deformational period. It is unlikely that Precambrian terranes did

¹ In some cases information concerning these criteria was not available in the publications from which the analyses were obtained. The necessary data were obtained through personal communications with the authors

Table 1. Application of Garnet-clinopyroxene thermometry in Granulite Terranes

Locality	Description	Data source	# Samples	Temperature (°C)	Dahl	Ellis and Green	Ganguly	Saxena
Adirondack Lowlands	amphibolite felsic granulite	Stoddard (1976) Bohlen and Essene (1980)	4	700	672–768 (725) ^a	652–734 (696)	760–804 (790)	730–813 (769)
Adirondack Highlands	felsic to mafic granulites	Bohlen and Essene (1980) Johnson and Essene (1982)	32	700–800	554–1276 (870)	690–941 (785)	776–1010 (902)	721–1064 (926)
Bukesfjorden Area, SW Greenland	mafic granulites	Wells (1979)	6	750–800	733–892 (800)	702–762 (733)	816–858 (839)	699–1005 (906)
Doubtful Sound, New Zealand	deep crustal mafic granulites	Oliver (1977)	5	750	787–1004 (933)	802–901 (868)	881–980 (944)	790–995 (851)
Furua Complex, Tanzania	felsic to mafic granulites (Zones B and C)	Coolen (1980)	30	750–800	690–950 (860)	736–813 (762)	801–943 (862)	824–951 (895)
Otter Lake Area, S. Quebec	felsic to mafic granulites	Perkins (1979)	7	675–700	612–737 (674)	663–697 (675)	754–791 (781)	837–896 (871)
Ruby Range, Montana	pelitic, mafic granulites, Fe-formation	Dahl (1980)	5	750	723–785** (752)	730–802 (764)	810–849 (830)	792–827 (808)
			4 (low Mn)	750	710–769 (745)	611–677 (648)	791–809 (800)	790–836 (805)

^a Values in parentheses are averages

^b The Ruby Range Montana is the field area in which Dahl's thermometer was empirically calibrated

not similarly evolve. In addition, rapid cooling seems unlikely since many granulite terranes were buried in excess of 25 kilometers. Nevertheless, petrologic studies in a number of granulite terranes suggest that a single high P – T regime is recorded in the mineral assemblages and chemistries without significant, pervasive retrogression. Evidence that minerals equilibrated during granulite facies metamorphism maintain their peak or near peak compositions during cooling and excavation is the general lack of zonation in pyroxenes, plagioclase, and garnets, in addition to the regular consistency of phase equilibria involving continuous and discontinuous reactions in a variety of lithologies. Mechanisms that might explain these phenomena might involve equilibration of the rocks during a fluid present prograde metamorphism with subsequent anatexis and intrusion of hydrous felsic magmas to higher levels, drying the rocks, and resulting in a vapor-absent retrograde metamorphism. This assumes that vapor-absent kinetics are several orders of magnitude slower than vapor-present conditions at granulite P and T . If such a mechanism were viable, it might explain the preservation of peak or near peak mineral chemistries for metamorphic assemblages of diverse chemistry.

Proper evaluation of metamorphic temperatures has been a matter of much recent discussion (Dahl 1979; Stoddard 1980; Coolen 1980). Some workers have determined metamorphic T by averaging the results from all applicable thermometers. Others have used all pertinent thermometers and chosen a temperature where the spread in temperatures from each thermometer overlap, the so-called consensus peak temperature. The averaging of thermometric data may be justified for a single thermometer if it can be demonstrated that the precision is poor but the average yields

a reasonably accurate value. The averaging of results from different thermometers seems totally unjustified, and at best can only yield a very approximate estimate of T . Similarly, the consensus temperature approach may yield some rough approximation of temperature but almost guarantees an imprecise and probably inaccurate temperature estimate, and precludes evaluation of T variation within a terrane. Metamorphic temperatures should be evaluated using the results of reaction equilibria and independent thermometry in an integrated fashion. With the above considerations in mind, we have attempted to evaluate the accuracy and precision of the four most recent and comprehensive formulations of the garnet-clinopyroxene geothermometer (Ellis and Green 1979; Ganguly 1979; Saxena 1979; Dahl 1980) in six different granulite terranes (Table 1).

The Adirondacks of upper New York State are a nearly ideal terrane in which to evaluate garnet-clinopyroxene thermometry. Garnet-clinopyroxene assemblages are common and span a wide range of compositions ($Mg/(Mg + Fe^{2+})_{cpx} = 0.09$ – 0.85). The pressure-temperature framework of Adirondack metamorphism has been well established using a variety of mineral systems. Pressures are well known and have been widely discussed (Bohlen et al. 1980b; Valley and Essene 1980; Bohlen and Boettcher 1981; Johnson and Essene 1982). Feldspar and oxide thermometry yield consistent and smoothly varying temperatures ranging from 600–650° C in the extreme northwest Adirondack Lowlands, to 750–800° C in areas surrounding the Marcy anorthosite, the Adirondack Highlands (Bohlen et al. 1980a). This regional picture is further corroborated by other thermometers. In the Balmat-Edwards district (NW Adirondacks) Brown et al. (1978) report a calcite-dolomite temperature of 625° C and just north of Mt. Marcy Valley and

Essene (1980) report coexisting akermanite-wollastonite-monticellite that requires $T = 750 \pm 30^\circ \text{C}$. In rocks adjacent to this locality, oxide and feldspar thermometry yield $770 \pm 30^\circ \text{C}$. Other temperature-sensitive systems support the regional trend defined by oxide and feldspar data. Valley and O'Neil (1981) show systematic, well-defined trends in fractionation of ^{13}C between calcite and graphite with the lowest fractionation occurring where oxides and feldspars indicate highest T and increasingly greater fractionations as inferred T decreases. In addition, a variety of phase equilibria in marbles, pelites, and orthogneisses are consistent with the oxide and feldspar data (Bohlen and Essene 1978b; Bohlen et al. 1980b; Valley and Essene 1980a, b). Recently, the oxide and feldspar T data have been criticized as being too low because of the uncertainty associated with the reintegration techniques necessary to account for the effects of retrograde intracrystalline features (Stoddard 1980) and because feldspar and oxide temperatures are below those obtained by pyroxene thermometry (Coolen 1980). Where temperature data are sparse, it is possible that the feldspar and oxide T could be somewhat low. In the area near Colton (Stoddard's field area) subsequent work (Edwards and Essene 1981) shows that oxide and feldspar temperatures are $700 \pm 20^\circ \text{C}$, in agreement with Stoddard and some $20\text{--}50^\circ \text{C}$ higher than the data of Bohlen et al. (1980a) that were based on only two temperature determinations, both $25\text{--}30 \text{ km}$ from Colton. However, similar criticism of the data for the central Adirondack Highlands is untenable. The widespread occurrences of phlogopite-calcite-quartz, tremolite-calcite-quartz, grossular-rich garnet-quartz, and the absence of metamorphic pigeonite (Podpora and Lindsley 1979) in ortho- and paragneisses place severe constraints on maximum T . The maxima are consistently within $20\text{--}30^\circ \text{C}$ above and below the T inferred from other thermometers. Hence, the phase equilibria support the premise that the temperature data of Bohlen et al. (1980a) are peak or very near peak metamorphic temperatures.

Electron microprobe analyses of 43 garnet-clinopyroxene pairs (Stoddard 1976; Bohlen and Essene 1980; Johnson and Essene 1982) have been used to calculate Adirondack temperatures. The results of the Ellis and Green, Ganguly, Saxena and Dahl thermometers are shown in Figs. 1, 2, 3, and 4, respectively, and summarized in Table 1.

Comparison of Figs. 1 through 4 indicates that the Saxena formulation of the garnet-clinopyroxene thermometer yields temperatures that appear to be much too high as do the results of the Ganguly and Dahl calibrations, although perhaps to a lesser degree. Of the three, the Dahl calibration is the least precise. However, the Ellis and Green calibration appears to yield temperatures with slightly greater precision and, apart from a few notable exceptions, considerably greater accuracy. Despite substantial imprecision and apparent inaccuracy, the Saxena, Ganguly and Dahl thermometers seem capable of sensing large variations in temperature ($80\text{--}100^\circ \text{C}$ or more) such as those that exist between the central and northwest Adirondacks. Such a relative temperature variation could also have been inferred from the K_D values of garnet-cpx pairs; 5 samples from the northwest have an average K_D of 7.3 while those in the central Adirondacks average 5.3.

There are several potential causes for the problems with precision and/or accuracy in these thermometer calibrations. We have attempted to evaluate the potential problems

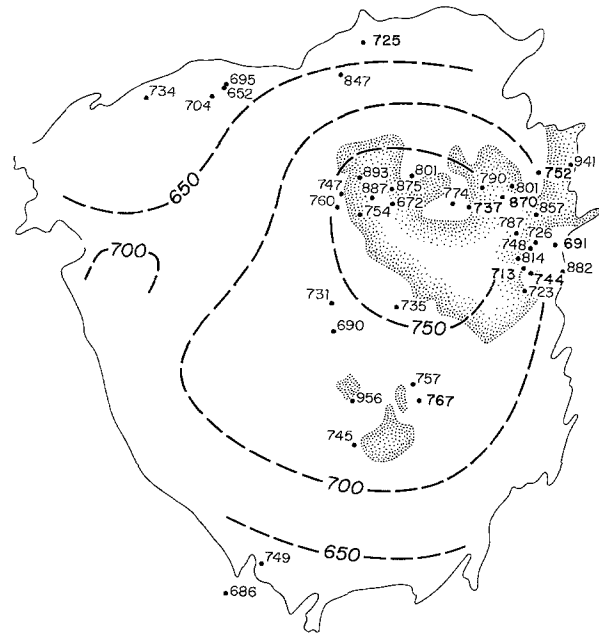


Fig. 1. Temperatures calculated from Ellis and Green formulation of garnet-clinopyroxene thermometry. Dashed curves are inferred isotherms of Bohlen et al. (1980a). Stippled areas are anorthosite masses. Map outlines the Precambrian terrane of Upper New York State

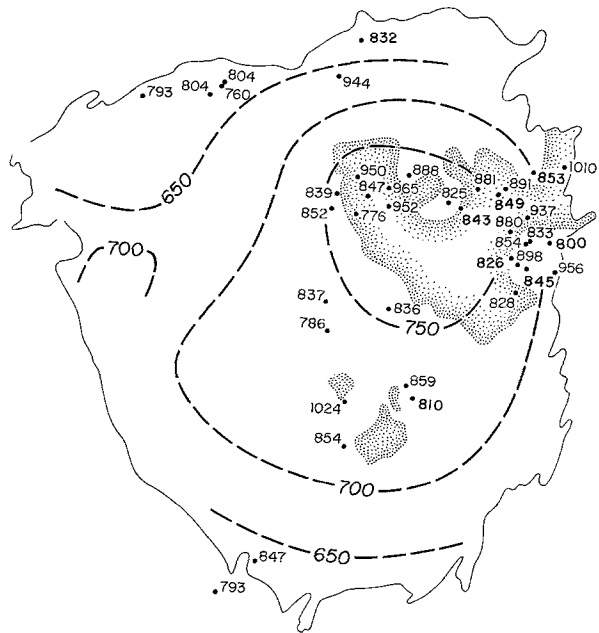


Fig. 2. Temperatures calculated from Ganguly formulation of garnet-clinopyroxene thermometry. Map outline, dashed curves and stippled areas same as in Fig. 1

arising from mineral zonation. The chemical profile of an Adirondack garnet is shown in Fig. 5. This profile was chosen from over a dozen different rocks, or in two cases, two profiles from different garnets in the same rock. It is similar to the other profiles but is exceptional in that it shows the *greatest* variation in compositions near the grain boundaries. It can be seen that there are very small compositional variations across the garnet. Almandine and pyrope components vary by $1\text{--}2 \text{ mol } \%$ with some of the

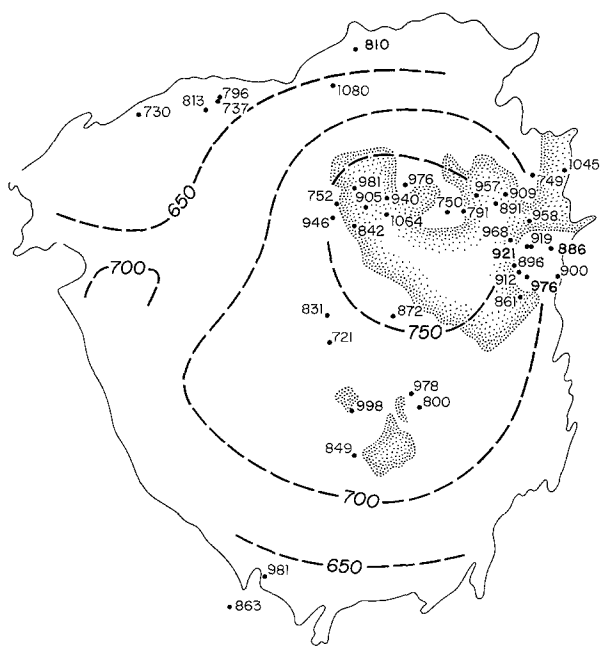


Fig. 3. Temperatures calculated from Saxena formulation of garnet-clinopyroxene thermometry. Map outline, dashed curves and stippled areas same as in Fig. 1

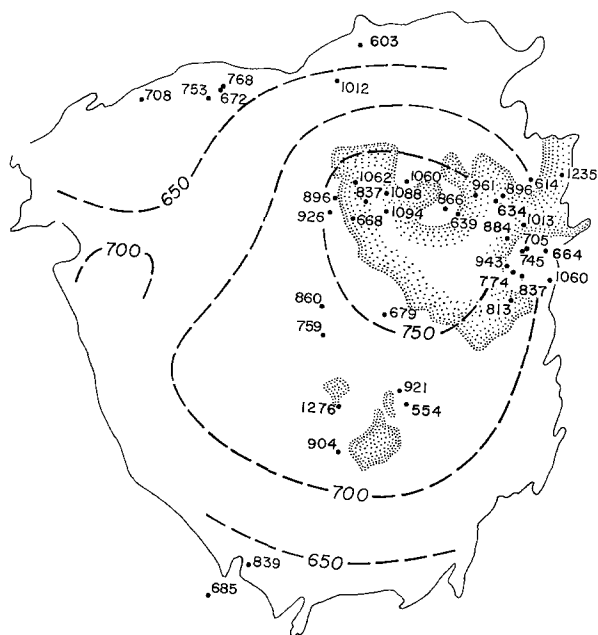


Fig. 4. Temperatures calculated from Dahl formulation of garnet-clinopyroxene thermometry. Map outline, dashed curves and stippled areas same as in Fig. 1

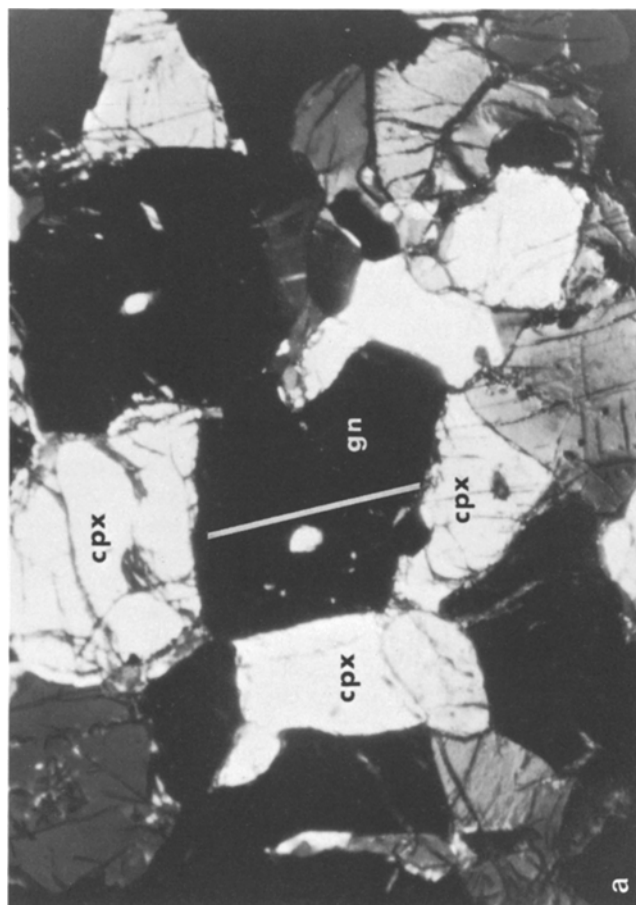
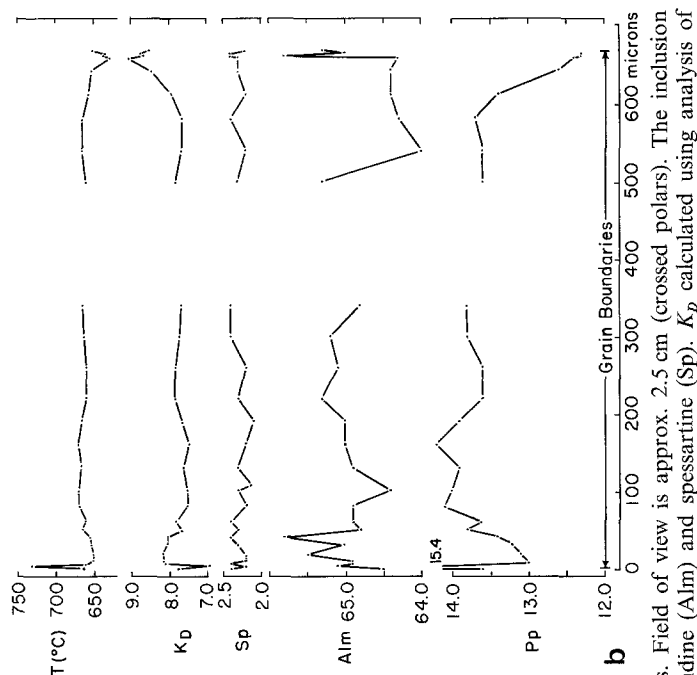


Fig. 5a, b. a Line of microprobe traverse across a garnet from an Adirondack orthogneiss. Field of view is approx. 2.5 cm (crossed polars). The inclusion in the center of the garnet is quartz. b Analyses of garnet in mole % pyrope (Pp), almandine (Alm) and spessartine (Sp). K_D calculated using analysis of nearby clinopyroxene; temperatures calculated from Ellis and Green for 27 points on traverse

variation (0.2–0.6 mol %) attributable to counting statistics. Spessartine and grossular components remain essentially constant. The largest variations occur within 10–30 microns of the grain boundary, possibly signaling localized retrogression. Although these variations are small in absolute terms, their effect on calculated temperatures can be substantial, as indicated in Fig. 5. Clinopyroxenes, on the

other hand, show remarkable homogeneity even near grain boundaries. Our analyses of Adirondack garnets represent averages of 6–10 points taken in areas away from the relatively inhomogeneous rims. Therefore, it is unlikely that much of the observed imprecision or inaccuracy can be attributed to the minor compositional variations found in Adirondack garnets. We have also attempted to evaluate

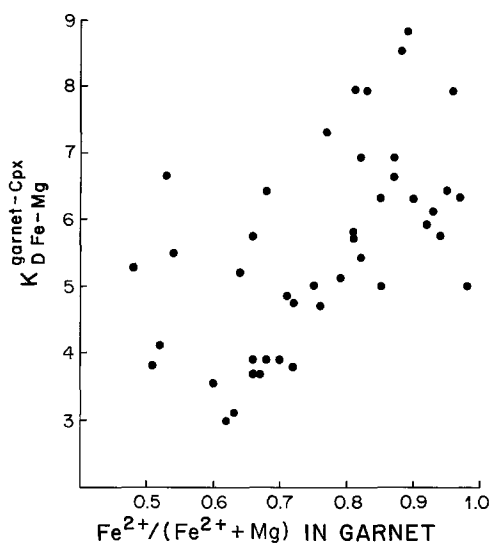


Fig. 6. $K_{D, Fe-Mg}^{garnet-cpx}$ vs. Fe/Mg ratio for Adirondack garnet-clinopyroxene pairs

any possible dependence of K_D on additional components such as Ca-, Ti-, Fe-Tschermaks, acmite, and jadeite components in clinopyroxenes that together can comprise up to 15% of some Adirondack clinopyroxenes. Simple plots of these components vs. K_D show no correlations. There may be a slight negative correlation between K_D and Ti-Tschermaks component (higher the component, the lower the K_D) although the spread in the data are large. Coolen (1980) noted a rough positive correlation of K_D with Ca-Tschermaks component. A similar correlation is not observed in the Adirondack data. Also the strong correlation between Mg/Fe²⁺ ratio and K_D reported by Bohlen and Essene (1980) is still evident from our larger data base (Fig. 6), although there is somewhat greater scatter in the data. Despite the spread in the data, there appears to be a tendency for more magnesian bulk compositions to yield lower K_D . It is possible that at least some of the problems of accuracy and precision are related to this effect.

Other factors potentially affecting the calculated temperatures are analytical errors and errors in the estimation of Fe³⁺. To date there is no systematic study comparing the estimated Fe³⁺ iron contents of minerals with analytical determinations. However, for the analyses used in this study, there is a good correlation between the amount of Fe³⁺ in garnet and the amount in clinopyroxene that, at least indirectly, supports the scheme by which Fe³⁺ is determined and means that calculated temperatures differ by only a small amount (<30° C) if one assumes either no Fe³⁺ or the estimated Fe³⁺ values. An error of 50% in the calculated Fe³⁺ contents of one of the minerals changes temperatures by less than 25° C. In a similar way, small analytical errors of the sort to be expected with analyses obtained through use of the electron microprobe do not dramatically affect the calculated temperatures. For example, a ±3% error in analysis of MgO in garnet changes the calculated temperature by ±15° C. Therefore, aside from the possible effect of Fe/Mg ratio, it appears that in the Adirondacks, at least, there are no obvious reasons (such as mineral zonation, affects of minor components or analytical errors) for the imprecision of the garnet-clinopyroxene thermometers or the large differences between the

results of the Dahl, Ganguly, Saxena calibrations and those of Ellis and Green.

There are six or seven garnet-clinopyroxene assemblages that yield unreasonably high temperatures in all four thermometer formulations. One is tempted to ascribe these anomalies to disequilibrium because the minerals have no unusual chemical characteristics that distinguish them from the other assemblages. However, distribution coefficients for Ca, Mn, Ti, etc. between garnet and clinopyroxene and other phases such as orthopyroxene, amphibole and plagioclase are similar to those in other rocks for which garnet-clinopyroxene temperatures are more reasonable. Even Mg/Fe distribution between orthopyroxene and clinopyroxene in these "anomalous" assemblages is essentially the same as that in the other assemblages, implying that the minerals in the assemblages are in equilibrium with respect to their Mg and Fe contents. Furthermore, pressures calculated from these "anomalous" assemblages using plagioclase-(orthopyroxene-clinopyroxene)-garnet-quartz geobarometry (Newton and Perkins 1982, Bohlen et al. 1983) agree well with the pressure values obtained from the other assemblages. Therefore, if the unreasonably temperatures are the result of disequilibrium, it is manifest in a subtle manner.

It is somewhat surprising that in the Adirondacks the garnet-clinopyroxene thermometer that is the most accurate is the one that considers the fewest variables. In order to determine if the trends seen in the results of these thermometers are specific to the Adirondacks or are general, we have applied the four garnet-clinopyroxene thermometers in five other granulite terranes for which sufficient, high-quality analytical data are available. Unfortunately, rigorous testing of the thermometers in other terranes is not always possible as a result of uncertainties in equilibration temperatures. Metamorphic temperatures in the granulite terranes of Greenland, Montana, New Zealand and Tanzania have been determined wholly or in large part by two-pyroxene geothermometry. The apparent undying faith in pyroxene thermometry is difficult to explain in light of several studies demonstrating both its inaccuracy and imprecision at metamorphic temperatures (Stormer and Whitney 1977; Lal et al. 1978; Bohlen and Essene 1979; Lindsley and Andersen 1983). These studies show that pyroxene geothermometry (Wood and Banno 1973; Wells 1977) yield scattered temperatures that generally are higher than other temperature data. Despite these problems, it is interesting to note that the trends observed in the Adirondacks are generally seen in other terranes. All thermometers seem to be imprecise although the Ellis and Green thermometer is substantially less so. In general, the Saxena temperatures are highest, well above the estimated equilibration temperatures (EET). The Ganguly and Dahl formulations also tend to give temperatures that appear to be too high. Ellis and Green temperatures, although somewhat scattered, are generally close to the EET, and in some cases, are in excellent agreement with other temperature data (Otter Lake, for example). Results from two field areas are of particular interest. In the Doubtful Sound terrane all garnet-clinopyroxene formulations give much greater temperatures than those inferred from Wood-Banno pyroxene thermometry. Secondly, data from the Ruby Range seem to indicate a marked effect of Mn on calculated Ellis & Green temperatures, suggesting that this thermometer may underestimate temperature when garnets contain greater than 10 mol % spessartine component. Study of Table 1 shows that in at

least these six granulite terranes, the garnet-clinopyroxene geothermometer of Ellis and Green appears to give the most satisfactory results. The other calibrations give highly erratic and generally inaccurate temperatures, and their use elsewhere in their present form is not recommended.

We emphasize that our analysis of these four thermometers applies only to granulites containing garnets and clinopyroxenes whose compositions can be well described by $(\text{Fe}-\text{Mg}-\text{Ca})_3\text{Al}_2\text{Si}_3\text{O}_{12}$ and $(\text{Ca}-\text{Fe}-\text{Mg})_2\text{Si}_2\text{O}_6$ respectively. The results of this study may not apply to rocks of greatly different thermal regimes and/or mineral chemistries. Indeed since the Ellis and Green thermometer does not consider the effects of large proportions of Na, Al and Mn in clinopyroxene or Mn in garnet, the Ganguly or Saxena formulations may ultimately be the most accurate and widely applicable after considerable adjustment of calibration parameters.

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