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Pyroxene Geothermometry of Some Granulite Facies Rocks

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Abstract. Wood-and-Banno temperatures for the coexisting pyroxenes of equilibrated metamorphic rocks in the hornblende granulite subfacies fall in the range 780–860° C. Minimum temperature estimates for granulites include 760–790° C, from the dehydration of hornblende to an orthopyroxene assemblage, and about 800° C, from other evidence. The pyroxene temperatures are generally consistent with these temperature estimates, and are certainly not too low or more than 50° too high. Pyroxene temperatures for the three subzones of Broken Hill granulites increase away from the orthopyroxene isograd and are sufficiently precise that the difference between the lowest and intermediate subzones is statistically significant. Temperatures for pyroxenes in pyroxene-granulite subfacies rocks are greater than 860° C. The internal consistency, precision and apparent accuracy of the Wood-and-Banno pyroxene geothermometer in the metamorphic temperature range make it an important tool.

Introduction

Phase equilibrium data allow broad constraints to be put on the conditions of formation of mineral assemblages. The compositions of coexisting minerals may permit a more precise estimate of these conditions. However, the widely used magnetite-ilmenite assemblage suffers re-equilibration during slow cooling [1—3], like metallic alloy mineral assemblages [4]. Because of low diffusion rates, pyroxene compositions tend to be fixed at or near peak temperatures. A semi-empirical expression for equilibrium temperature in terms of the compositions of coexisting orthopyroxene and augite has been developed from experimental data [5]. A computer program, available from this author on request, has been written for this Wood-and-Banno pyroxene geothermometer using their assumptions on site occupancies and their final equation number 27 [5]. The program has been used to obtain pyroxene temperatures for terrestrial granulites, described below, and also for lunar rocks [4].

Discussion

Temperature data for the Broken Hill hornblende granulites of New South Wales [6–8] are given in Table 1. These granulites occur adjacent to amphibolite-facies rocks in which muscovite is replaced by sillimanite and orthoclase. Assuming water pressure equal to total pressure within the amphibolite facies, the intersection of the muscovite dehydration curve [9] with the andalusite-sillimanite inversion curve defines a minimum temperature for these rocks. This is about 600° C, using the data of [10], or about 625° C, using the data of [11]. The intersection of the muscovite dehydration curve with the curve for beginning of melting

Table 1. Temperature estimates for Broken Hill rocks [3, 6, 7, 8]. For explanation see text

Facies	Zone	Temperature (° C; s.e.)	Method
Granulite	3	843	
	2	838 ± 8	Pyroxene geothermometer
	1	808 ± 14	
Orthopyroxene isograd		<790, ∼ 760	Hornblende dehydration/ melting curves
Amphibolite			
Sillimanite-orthoclase isograd		>680 or >620, ∼660	Muscovite dehydration/ andalusite inversion/ melting curves

of granite [12] defines an additional permissible temperature of 660° C. Possible conditions for the transition from the amphibolite to granulite facies were defined by the experimental dehydration of Broken Hill hornblende to an orthopyroxene assemblage [8]. The dehydration took place in the rocks with no apparent melting of the hornblende or of granodioritic gneisses [7]. The temperature of this orthopyroxene isograd was therefore less than about 790° C but not necessarily less than 760° C, from the intersection of the hornblende dehydration curve with the hornblende melting curve [8] and the granite melting curve [12], at a water pressure less than total pressure.

Temperatures calculated for the pyroxenes in the Broken Hill granulites, using the data of [6], are 808 ± 14° C (s.e.) for the lower zone, 838 ± 8° C for the intermediate zone and 843° C for the higher zone. These estimates exceed those for the orthopyroxene isograd, and increase away from it despite the fact that simple partition coefficients for pyroxenes do not vary systematically across these zones [3]. The pyroxene temperatures are internally consistent and very precise. The estimates for the lower and intermediate zones were found by T-test to be significantly different at the 90% level. Since the pyroxene temperatures are higher than those for the orthopyroxene isograd they are broadly reasonable. However, in so far as the temperatures for the orthopyroxene isograd are maximum estimates, it is conceivable that the pyroxene temperatures are higher than true temperatures, perhaps by as much as 50° C.

Pyroxene temperatures for other hornblende-granulite subfacies rocks are given in Table 2. They include 784 ± 8° C for pyroxene gneiss from Finland [13], 840 ± 5° C for Quairading mafic granulites, W. Australia [14] and 845 ± 12° C for Amaravathi granulites, India [15]. The pyroxenes of charnockites yield temperatures of 841 ± 11° C [4] for Madras [16] and 859 ± 9° C for Kondapalli, India [17]. These temperatures in the range 780–860° C are generally consistent with the Broken Hill data and also with estimates for granulite-facies temperatures from other lines of evidence. Granulites such as these tend to be associated with granites or represent the residue of partial melting [18]. From the discussion above, hornblende dehydration therefore took place at a minimum of 760° C and probably at about 790° C. Such arguments led to a minimum estimate of 800° C

Table 2. Comparison of pyroxene temperatures with minimum temperature estimates for granulite facies rocks

Pyroxene temperature (°C; s.e.)	Rock type, location, reference	Minimum temperature estimate (° C)	Location, method, reference
Pyroxene-granulite subfacies			
867 ± 9	Pyroxene gneiss, Delaware [22]		
898 ± 4	Recrystallized norite, Quebec [23]		
hornblende-granulite subfacies			
784 ± 8	Pyroxene gneiss, Finland [13]	760	Adirondacks, perthite-garnet [2]
840 ± 5	Granulite, W. Australia [14]	800	Adirondacks, hornblende dehydration [2]
845 ± 12	Granulite, S. India [15]	800	Adirondacks, corona assemblages [19]
841 ± 11[a]	Charnockite, Madras [16]	750–820	Norway, hornblende dehydration [20]
859 ± 9	Charnockite, S. India [17]	800	Norway, fluid inclusions [21]
857 ± 11	Recrystallized norite, Quebec [23]		

[a] From [5].

for Adirondacks granulites [2]. Additional estimates of minimum temperatures for Adirondacks rocks are 760°C from perthite-garnet assemblages [2] and 800°C from corona assemblages [19]. Hornblende dehydration was estimated to have occurred at 750–820°C in Norwegian granulites [20] while CO_2-rich fluid inclusions in the same rocks indicate temperatures of about 800°C [21]. The pyroxene temperatures are generally higher than these minimum estimates for the granulite facies but, since the rocks in question are not immediately adjacent to amphibolite-facies rocks, the temperatures need not be close to the minimum estimates. The pyroxene temperatures therefore appear reasonably accurate and are certainly less than 50°C too high.

Pyroxenes from the hornblende-free Wilmington gneiss complex, Delaware [22] yield a temperature of 867 ± 9°C, which is higher than the estimates for the hornblende-granulite subfacies. Recrystallized norites in the Grenville of Quebec [23] yield pyroxenes temperatures of 857 ± 11°C for hornblende-granulite subfacies terrain (Belleau-Desaulniers area) and 898 ± 4°C for pyroxene-granulite subfacies terrain (Grenville Township). Thus hornblende breakdown appears complete at temperatures of about 860°C in granulite facies rocks.

The hornblende-granulite subfacies rocks described above have pyroxene temperatures in the range 760 to 860°C, despite a wide range of whole rock and pyroxene compositions. For three of these areas, other rocks are present which give pyroxene temperatures discordant with those of the main rock type. These are ultramafic granulites at Quairading [14] which yield 893 ± 19°C; dikes and lenses, principally ultramafic, among the massive charnockites at Kondapalli [17] which yield 958 ± 43°C; and a charnockite among the granulites at Amaravathi [15] which yields a temperature of 888°C. It is possible that all these temperatures represent some partial equilibration from original igneous temperatures. Such a process might be expected for late igneous rocks cooling in a metamorphic environment. An igneous temperature (1059°C) was obtained for coarse-grained norite associated with recrystallized norite in Grenville Township [23]. The Mecklenburg gabbro [24] yields a pyroxene temperature of 922 ± 9°C. This is lower than those typical of mafic igneous rocks, e.g. 1005–1150°C [5] for Bushveld cumulates, 1000–1060°C for the mafic norite of the Sudbury Nickel Irruptive [25], and 1164°C for the Guadalupe hypersthene gabbro [24]. The temperature estimate and reaction textures [24] suggest that the Mecklenburg gabbro has undergone a degree of sub-solidus re-equilibration. Adjacent recrystallized and unrecrystallized metagabbro [24] yield still lower temperatures, 864 ± 10°C and 876 ± 7°C respectively. However, pyroxene compositions were not completely re-equilibrated, for the local metamorphic rocks are upper amphibolite facies only. In these cases, (partial) preservation of igneous textures supports the re-equilibration hypothesis. In the case of the rocks occurring with the granulites, an origin as late igneous rocks, partly re-equilibrated, is possible and would explain the discordant temperatures.

Conclusions

1. Wood-and-Banno pyroxene temperatures for granulites are internally consistent, precise and generally concordant with other temperature estimates. They are certainly not too low or more than 50° too high.

2. Hornblende-granulite subfacies rocks crystallized at temperatures in the range 780–860°C and pyroxene-granulite subfacies rocks at higher temperatures.

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