

Pyroxene exsolution in granulites from Fyfe Hills, Enderby Land, Antarctica: Evidence for 1000°C metamorphic temperatures in Archean continental crust

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ABSTRACT

Orthopyroxene (Opx) and augite (Aug) in metasedimentary and meta-igneous gneisses in a supracrustal succession at Fyfe Hills, Enderby Land, Antarctica, exhibit intimate exsolution intergrowths. In magnesian assemblages, exsolution lamellae occur only on 100 as a result of exsolution of Opx from Aug and Aug from Opx. In more Fe-rich assemblages, exsolution lamellae occur on both 001 and 100 in Opx. The 001 lamellae indicate exsolution involving pigeonite (Pgt) subsequently “inverted” to Opx and Aug. In intermediate assemblages, Opx-Aug intergrowths are blebby rather than lamellar, a feature attributed to the decomposition of primary metamorphic Pgt in the three-phase field of Opx-Pgt-Aug. The textural relations and compositional data suggest the following phase relations at peak conditions: Opx-Aug (for $X_{\text{Fe}}^{\text{Opx}} < 0.43$), Opx-Aug-Pgt (for $X_{\text{Fe}}^{\text{Opx}} = 0.5-0.43$), Opx-Pgt (for $X_{\text{Fe}}^{\text{Opx}} > 0.5$), Aug-Pgt (for $X_{\text{Fe}}^{\text{Aug}} > 0.48$), where $X_{\text{Fe}} = \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$. Application of Lindley's (1983, *American Mineralogist*, 68, 477–493) phase diagram at the relevant pressure (9 kbar) implies a peak metamorphic temperature of at least 1000°C.

INTRODUCTION

The Napier Complex granulites in Enderby Land, Antarctica, contain a number of exceptionally rare assemblages indicative of exceedingly high temperature metamorphism, including sapphirine + quartz + osumilite (Ellis et al., 1980; Grew, 1982); sapphirine + orthopyroxene + mesoperthite + quartz (Sandiford, 1985a); and pigeonite (now inverted) + magnetite + quartz (Grew, 1982). These assemblages imply that the Napier Complex represents one of the highest-temperature granulite terranes known, along with the granulites of Labwor Hills, Uganda (Nixon et al., 1973); Wilson Lake, Canada (Morse and Talley, 1971); and Scourie, Scotland (Barnicoat and O'Hara, 1979). Establishing the temperatures at which such granulite terranes formed is particularly important in understanding granulite-facies metamorphism and its role in crustal growth and differentiation. In this contribution we determine the peak metamorphic temperatures recorded by the Napier Complex granulites using constraints imposed by compositional and textural relations in complexly exsolved metamorphic pyroxenes from the Fyfe Hills region of the Napier Complex. The texturally based approach to thermometry used herein circumvents some of the problems common in conventional thermometry that are caused by chemical re-equilibration during slow cooling of rocks from very high temperatures (Esene, 1982; Powell, 1985).

GEOLOGIC SETTING OF THE FYFE HILLS GRANULITES

The Fyfe Hills occur near the western boundary of an Archean gneissic terrane termed the Napier Complex

(Sheraton et al., 1980). Two distinct lithologic associations are found in the Napier Complex (Sheraton and Black, 1983). The oldest association consists of pelitic, psammitic, and ferruginous metasedimentary rocks intimately interlayered with meta-igneous rocks of presumed volcanic origin. The younger association is an intrusive meta-igneous sequence that is believed to have been emplaced immediately prior to or during peak metamorphism. Although the meta-igneous rocks from both lithologic associations are similar petrographically, they are readily separated by their distinctive field occurrence and trace-element geochemistry (Sheraton and Black, 1983; Sandiford and Wilson, 1986). All pyroxene-bearing rocks discussed in this paper apart from sample R25384B belong to the older supracrustal association. Sample R25384B is interpreted as a dike, intruded and isoclinally folded prior to the peak metamorphism (Sandiford and Wilson, 1984).

Sapphirine-quartz assemblages in the metapelites are widespread in the central and southwest part of the Napier Complex (Sheraton et al., 1980) and indicate that temperatures throughout this region exceeded 800–850°C (Newton, 1972; Newton et al., 1974). On the basis of the distribution of osumilite and equivalent parageneses in bulk compositions approaching KFMAS, Sandiford (1985a) argued that metamorphic temperatures were approximately equivalent across the region in which sapphirine-quartz occurs, an area of about 100-km diameter (see also Grew, 1982). These assemblages do, however, indicate a systematic increase in pressure from northeast to southwest across the Napier Complex, suggesting that the current exposure of the Napier Complex represents an oblique profile through the lowermost part of an Archean continental crust (Sandiford, 1985a).

The quantification of the temperature of formation of this lower-crustal, nearly isothermal section has proved difficult. Estimates based on pyroxene thermometry after Wells (1977) are in the range 780–980°C (Ellis, 1980; Grew, 1980; Black et al., 1983; Sandiford, 1985a). The lower end of this range is defined by the estimates of Grew (840–890°C) and Sandiford (780–920°C), neither of whom attempted to reintegrate the composition of the ubiquitous exsolution lamellae found in the highest-grade pyroxene assemblages. Neither Ellis (1980) nor Black et al. (1983) indicated whether their temperature estimates were based on reintegrated pyroxene compositions. Given that experimentalists claim that they achieve equilibrium in this system at temperatures as low as 1000°C, calculated temperatures of this order in slowly cooled rocks are unlikely to reflect peak metamorphic temperatures. Thus, the significance of published pyroxene thermometry in Napier Complex gneisses must be questioned, although the estimates of Grew (1980) and Sandiford (1985a) may provide absolute minima.

Pressures calculated from the garnet-aluminosilicate-plagioclase-quartz barometer (Newton and Haselton, 1981) and the garnet-orthopyroxene-plagioclase-quartz barometer (Newton and Perkins, 1982) suggest that the Fyfe Hills granulites equilibrated at 9 kbar (Sandiford, 1985a).

PYROXENE ASSEMBLAGES AT FYFE HILLS

Because of the extremely anhydrous nature of the Napier Complex granulites, pyroxene forms a common component of both meta-igneous and metasedimentary rock types. In the supracrustal sequence at Fyfe Hills, orthopyroxene and clinopyroxene occur together in ferruginous metasedimentary rocks (typically composed of subequal proportions of pyroxene, magnetite, and quartz) and in basic and intermediate meta-igneous gneisses presumably derived from volcanic rocks (Sandiford and Wilson, 1986). Representative whole-rock analyses of the assemblages described herein are presented in Table 1. Owing to this diversity of bulk composition, two-pyroxene assemblages exhibit a wide range of X_{Fe} [=Fe²⁺/Mg + Fe²⁺] with X_{Fe} ranging from 0.14 to 0.70. All samples with coexisting orthopyroxene (Opx) and augite (Aug) show evidence of exsolution involving Opx and Aug and in some cases pigeonite (Pgt). The extent of exsolution and the textural complexity of the exsolution intergrowths are, in a general fashion, dependent on the X_{Fe} of the participant pyroxenes, suggesting that the highest-temperature Fe-rich pyroxenes showed considerable solid solution into the interior of the pyroxene quadrilateral, with the more Fe-rich bulk compositions “seeing” the stability field of pigeonite.

In the following discussion we attempt to reconstruct the peak metamorphic phase relations for the pyroxenes in these rocks through the interpretation of exsolution textures. This reconstruction provides a useful basis for evaluating the peak temperature of metamorphism of the Fyfe Hills granulites, a basis that is, to a large extent, independent of the pronounced Fe-Mg exchange that con-

Table 1. Representative XRF whole-rock analyses of pyroxene-bearing rocks described in this paper; all Fe as Fe₂O₃

	R25402	R31031
SiO ₂	51.23	42.43
TiO ₂	0.53	0.35
Al ₂ O ₃	14.17	0.61
Fe ₂ O ₃	10.30	49.15
MnO	0.17	0.07
MgO	8.06	1.94
CaO	11.32	1.24
Na ₂ O	2.12	0.15
K ₂ O	0.33	0.01
P ₂ O ₅	0.06	0.04
LOI	-0.22	3.93
Total	99.35	99.99

tinued to much lower temperatures during cooling and subsequent re-equilibration.

The samples described herein were collected from the Fyfe Hills and the adjacent islands of Khmara Bay over an area approximately 200 km² in size. This region forms a coherent tectonic unit (Sandiford and Wilson, 1984), and the distribution of assemblages in metapelites (which include sapphirine + garnet + quartz and sillimanite + hypersthene + quartz) suggests that temperatures at the peak of metamorphism did not vary significantly throughout this region (Sandiford, 1985a).

ANALYTICAL TECHNIQUES

Electron-microprobe analyses for orthopyroxene and clinopyroxene from two-pyroxene assemblages are presented in Tables 2 and 3, respectively. Analyses were performed on the Melbourne University JXA-5A wavelength-dispersive instrument operating at 15 kV and with a beam width of 10 μm. The raw data were reduced according to the method of Ferguson and Sewell (1980). The analyses presented in Tables 2 and 3 represent individual spot analyses of pyroxenes. Except where otherwise indicated, the analyses represent the composition of the host pyroxene. No attempt has been made to reintegrate the composition of lamellae with hosts in these analyses. Structural formulae for pyroxenes have been recalculated according to the method of Lindsley (1983).

PETROGRAPHY OF PYROXENE-EXSOLUTION INTERGROWTHS

Three distinct types of pyroxene-exsolution intergrowth occur in the Fyfe Hills gneisses (Figs. 1–3). Each type is restricted to a distinct compositional range as indicated by the X_{Fe} of the coexisting pyroxenes.

Pyroxene-exsolution textures in Mg-rich rocks

In the most magnesian rocks that contain primary coarse-grained Opx and Aug, the Opx has fine exsolution lamellae

Table 2. Electron-microprobe analyses of orthopyroxenes, recalculated according to Lindsley (1983)

	R25402 host	R31096 host	R25812 host	R25812 lam	R25547 host	R25384 host	R25390 lam	R25393 lam	R31031 lam	R25384 lam	R25699 lam	R25693 host
SiO ₂	51.20	50.45	51.31	50.81	49.09	48.98	49.35	48.88	49.63	48.47	48.89	48.35
TiO ₂	0.08	0.05	0.12	0.00	0.01	0.10	0.01	0.00	0.03	0.11	0.07	0.07
Al ₂ O ₃	1.32	1.39	0.98	0.65	1.00	0.76	0.56	0.73	0.25	0.89	0.07	0.05
Fe ₂ O ₃	0.55	3.03	2.74	0.67	1.79	1.91	2.76	1.85	0.00	0.76	0.56	1.23
FeO	26.48	25.01	26.61	31.06	32.44	32.56	33.53	34.52	37.84	37.34	39.08	39.84
MnO	0.44	0.55	0.24	0.31	0.45	0.34	0.31	0.24	0.23	0.59	0.03	0.14
MgO	18.88	18.69	19.03	16.08	13.97	13.96	13.71	12.81	11.13	10.82	10.49	9.45
CaO	0.56	0.88	0.54	0.46	0.61	0.68	0.58	0.67	0.90	0.65	0.56	0.68
Na ₂ O	0.00	0.08	0.00	0.03	0.03	0.00	0.00	0.00	0.06	0.00	0.00	0.04
Total	99.52	100.12	101.57	100.07	99.39	99.29	100.81	99.70	100.07	99.64	99.75	99.84
Si	1.9600	1.9268	1.9359	1.9764	1.9506	1.9506	1.9458	1.9550	1.9959	1.9638	1.9877	1.9793
Ti	0.0023	0.0014	0.0034	0.0000	0.0003	0.0030	0.0003	0.0000	0.0009	0.0034	0.0021	0.0022
Al	0.0596	0.0626	0.0436	0.0298	0.0468	0.0357	0.0260	0.0344	0.0119	0.0425	0.0034	0.0024
Fe ³⁺	0.0158	0.0870	0.0778	0.0196	0.0537	0.0572	0.0818	0.0556	0.0000	0.0233	0.0170	0.0378
Fe ²⁺	0.8479	0.7987	0.8398	1.0103	1.0779	1.0845	1.1056	1.1546	1.2727	1.2653	1.3288	1.3639
Mn	0.0143	0.0178	0.0077	0.0102	0.0151	0.0115	0.0104	0.0081	0.0078	0.0202	0.0010	0.0049
Mg	1.0771	1.0638	1.0700	0.9322	0.8273	0.8285	0.8056	0.7636	0.6671	0.6533	0.6356	0.5766
Ca	0.0230	0.0360	0.0218	0.0192	0.0260	0.0290	0.0245	0.0287	0.0388	0.0282	0.0244	0.0298
Na	0.0000	0.0059	0.0000	0.0023	0.0023	0.0000	0.0000	0.0000	0.0047	0.0000	0.0000	0.0032
X	0.4405	0.4288	0.4397	0.5201	0.5658	0.5669	0.5785	0.6019	0.6561	0.6595	0.6764	0.7029
wo	0.01202	0.01983	0.01180	0.00990	0.01382	0.01542	0.01322	0.01518	0.01964	0.01474	0.01239	0.01543

Note: Rocks R25402, R31096, and R25812 contain pyroxenes having only 100 exsolution lamellae; rocks R25547 and R25384 contain Opx with blebby Aug; and the remaining rocks contain pyroxenes with coarse 001 lamellae of Aug and Opx (after Pgt).

Table 3. Electron-microprobe analyses of clinopyroxenes, recalculated according to Lindsley (1983); see note, Table 2

	R25402 host	R31096 host	R25812 host	R25547 bleb	R25384 bleb	R25390 host	R25393 host	R31031 host	R25384 host	R25699 host	R25693 lam
SiO ₂	51.10	49.95	50.83	51.04	50.01	50.56	49.70	51.33	49.32	50.94	50.89
TiO ₂	0.25	0.29	0.15	0.10	0.29	0.12	0.08	0.01	0.24	0.00	0.00
Al ₂ O ₃	2.19	3.20	2.46	1.79	1.93	1.74	1.81	0.44	2.06	0.18	0.05
Fe ₂ O ₃	2.05	2.85	2.55	2.39	2.12	3.10	1.42	2.31	2.35	2.29	1.54
FeO	8.97	7.88	10.29	12.14	12.55	12.47	14.47	15.79	15.51	15.35	17.19
MnO	0.19	0.24	0.12	0.21	0.17	0.12	0.09	0.10	0.27	0.14	0.15
MgO	12.62	11.99	11.41	10.29	9.93	10.29	9.47	8.98	8.15	8.87	8.39
CaO	21.35	21.67	21.34	21.47	20.96	21.68	21.07	21.03	20.44	22.03	21.64
Na ₂ O	0.50	0.59	0.61	0.63	0.60	0.40	0.23	0.55	0.58	0.30	0.18
Total	99.23	98.66	99.76	100.06	98.56	100.48	98.34	100.54	98.93	100.10	100.02
Si	1.9332	1.9009	1.9269	1.9459	1.9391	1.9278	1.9437	1.9767	1.9327	1.9737	1.9831
Ti	0.0071	0.0083	0.0043	0.0029	0.0085	0.0034	0.0024	0.0003	0.0071	0.0000	0.0000
Al	0.0977	0.1436	0.1099	0.0805	0.0882	0.0782	0.0835	0.0200	0.0952	0.0082	0.0023
Fe ³⁺	0.0585	0.0816	0.0726	0.0685	0.0618	0.0889	0.0419	0.0671	0.0693	0.0669	0.0451
Fe ²⁺	0.2839	0.2507	0.3262	0.3871	0.4071	0.3978	0.4733	0.5084	0.5084	0.4972	0.5601
Mn	0.0061	0.0077	0.0039	0.0068	0.0056	0.0039	0.0030	0.0033	0.0090	0.0046	0.0050
Mg	0.7115	0.6800	0.6446	0.5847	0.5738	0.5847	0.5520	0.5154	0.4760	0.5122	0.4873
Ca	0.8654	0.8836	0.8668	0.8771	0.8708	0.8857	0.8829	0.8678	0.8583	0.9146	0.9036
Na	0.0367	0.0435	0.0448	0.0466	0.0451	0.0296	0.0174	0.0411	0.0441	0.0225	0.0136
X	0.2852	0.2694	0.3360	0.3984	0.4150	0.4048	0.4616	0.4966	0.5165	0.4926	0.5348
wo	0.4247	0.4223	0.4235	0.4377	0.4360	0.4250	0.4244	0.4414	0.4246	0.4464	0.4428

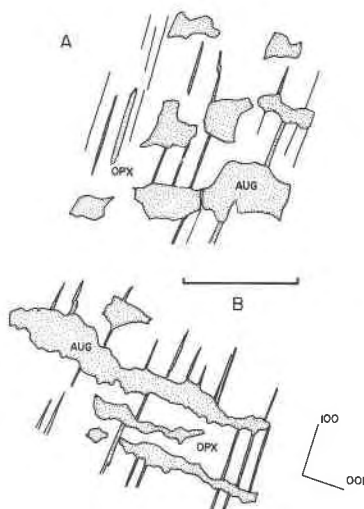


Fig. 1. Exsolution texture in R25547 showing blebby exsolution of Aug (stippled) in Opx host, with later augite lamellae on 100. Note the elongation of Aug blebs parallel to 001 in B. The pyroxene grain has the bulk composition of, and is believed to be derived from, primary Pgt. The bar scale represents 1 mm.

of Aug on (100) and the coexisting Aug has fine exsolution lamellae of Opx on (100). The proportion of exsolution lamellae to host never exceeds 5% in the primary Aug and 2% in the primary Opx. In contrast to the more Fe-rich

assemblages, there is no textural evidence that Pgt was stable in the primary metamorphic assemblage or that it developed during the exsolution history of these assemblages. These intergrowths are derived from primary coexisting Opx and Aug and are restricted to rocks in which the pyroxenes (host pyroxene without lamellae) have the composition $X_{\text{Fe}}^{\text{Opx}} < 0.44$ and $X_{\text{Fe}}^{\text{Aug}} < 0.34$.

Pyroxene-exsolution textures in rocks of intermediate composition

Rocks of intermediate Mg content contain both primary coarse-grained Opx with a small percentage of thin 100 Aug lamellae, as described for Mg-rich rocks, and a pyroxene intergrowth consisting of blebs of Aug up to 1 mm across in an Opx host (Fig. 1). The Aug blebs are typically blocky, or are elongated parallel to (100) or parallel to a plane at a high angle to (100), presumably (001). Fine 100 Aug lamellae occur in the Opx host, whereas very fine 100 Opx lamellae occur in the Aug blebs. The proportion of Aug bleb to Opx host in individual aggregates is approximately 1:3.7 (the average of estimates from five grains), indicating qualitatively that the bulk composition of the aggregates correspond to Pgt. In the two rocks found with the blebby exsolution texture, the Opx hosts have the compositions $X_{\text{Fe}}^{\text{Opx}} = 0.57$, and the Aug blebs have the composition $X_{\text{Fe}}^{\text{Aug}} = 0.41$. There is no difference in composition between Aug blebs and Aug lamellae.

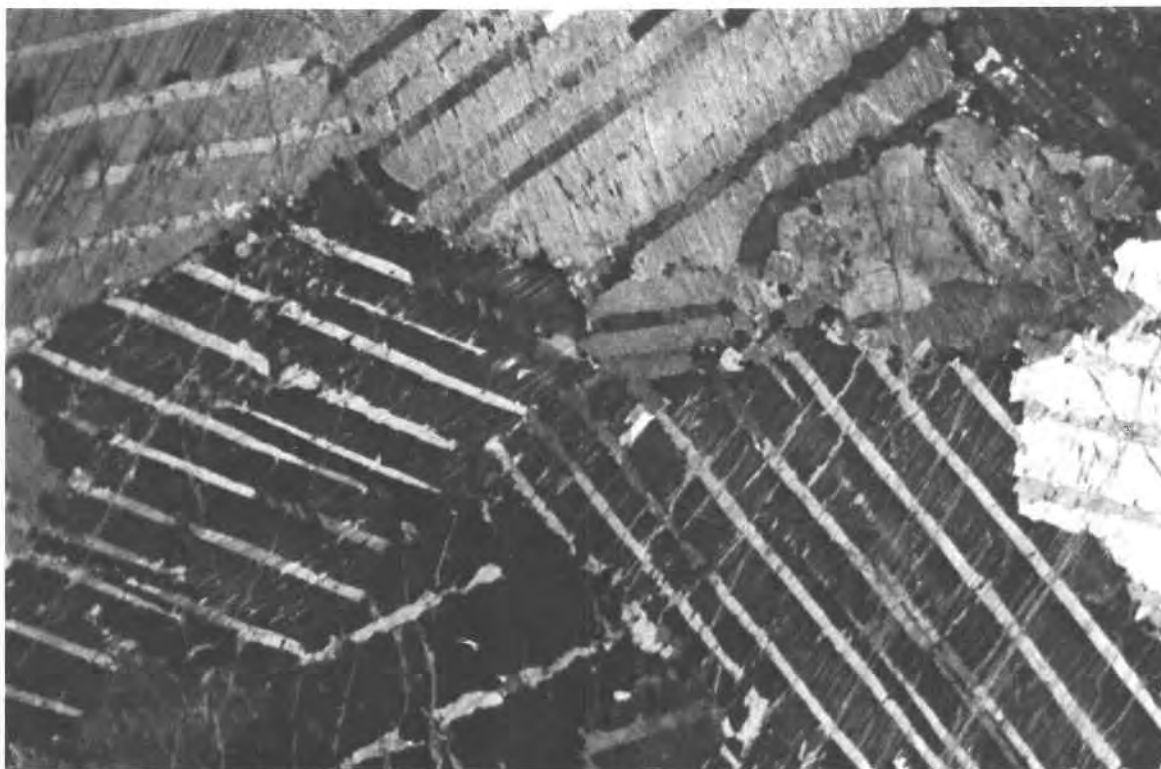


Fig. 2. Exsolution texture in pyroxene aggregate in R25699. The exsolution history of these grains involved the formation of broad 001 lamellae of Pgt in the primary subcalcic Aug. Subsequently, the Pgt lamellae decomposed to Opx and Aug. Finer 100 lamellae of Opx in Aug and Aug in Opx were then developed. Note the absence of exsolution-free grains along the boundaries of the large exsolved grains, indicating that granule exsolution was not a significant process. Photomicrograph is 3 cm wide.



Fig. 3. SEM back-scattered electron image of exsolution texture in a pyroxene grain in R31031. Aug (dark colored) and Opx (light colored) form broad lamellae subparallel to 001 and have subsequently exsolved finer 100 lamellae. Very fine "001" lamellae in the Aug have been identified as Pgt. Primary pyroxene was a subcalcic Aug.

Pyroxene-exsolution textures in Fe-rich rocks

In the most Fe-rich rocks, pyroxene-exsolution intergrowths contain broad lamellae up to 0.5 mm across on a plane close to (001) (the "001" lamellae of Robinson et al., 1971; Robinson, 1980; Figs. 2–3). The lamellae may consist either of Opx in an Aug host, or vice versa, and in both cases both the host and "001" lamellae contain finer (<20 μm wide) 100 lamellae of the coexisting pyroxene. In intergrowths in which Aug is the host, the ratio of Aug to Opx varies from 3:1 to 1:1; in intergrowths in which Opx is the host, the ratio of Aug to Opx is typically about 1:4. Because of bulk-composition arguments and the fact that "001" exsolution between Opx and Aug is not allowed (Robinson et al., 1971; Robinson, 1980), all exsolution intergrowths involving "001" lamellae must have involved Pgt. In pyroxene aggregates with "001" lamellae, the Aug component has compositions with $X_{\text{Fe}}^{\text{Aug}} > 0.46$, and the Opx component has compositions with $X_{\text{Fe}}^{\text{Opx}} > 0.58$.

INTERPRETATION OF THE EXSOLUTION TEXTURES

The exsolution textures in the Fyfe Hills pyroxene indicate that at peak conditions the stable assemblages included Opx-Aug in Mg-rich assemblages and Pgt-Aug and Opx-Pgt in intermediate and Fe-rich assemblages.

The exsolution features in primary Opx-Aug assemblages can be attributed to the widening of the pyroxene solvus with decreasing temperature without any change in stability relations among quadrilateral pyroxene phases. This is consistent with the primary Opx-Aug assemblages occurring in the most Mg-rich assemblages (with $X_{\text{Fe}}^{\text{Opx}} < 0.44$). The exsolution features in the most Fe-rich rocks can be attributed to the widening of the two-phase Aug-Pgt field with decreasing temperature, with exsolution taking place prior to the decomposition of Pgt to Aug and Opx.

The blebby intergrowths in the rocks of intermediate Mg content are regarded as the product of decomposition of Pgt to Opx and Aug as the three-phase field Pgt-Opx-

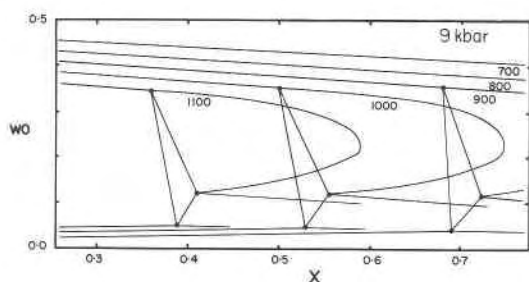


Fig. 4. Schematic phase relations among pyroxenes in CaO-MgO-FeO-SiO₂ in terms of $Wo = Ca/(Ca + Mg + Fe)$ and $X = Fe/(Fe + Mg)$, in the form of isothermal sections for a series of temperatures (in degrees Celsius) constructed for 9 kbar (after Lindsley, 1983).

Aug tracks to more Fe-rich compositions during cooling. Thus, the blebby intergrowth is a reaction texture rather than an exsolution texture. Ishii and Takeda (1974) proposed a similar explanation for blebby intergrowths in "inverted" pigeonites from Kintokisan in Japan. The absence of lamellar exsolution prior to decomposition of the Pgt, suggests that these assemblages crystallized close to the three-phase field Opx-Aug-Pgt at peak temperatures. As textural evidence for the coexistence of the three primary phases has not been found, this interpretation must remain somewhat conjectural. However, it is supported by the general compositional considerations provided by other exsolution textures; the less Fe-rich compositions have only primary Opx and Aug whereas the more Fe-rich compositions have either primary Opx and Pgt or Aug and/or Pgt. Moreover, the nearly identical compositions of the pyroxenes in the two assemblages is consistent with this explanation.

The compositional dependence of the exsolution intergrowths is readily explained with the aid of the experimentally determined phase relations for quadrilateral-system pyroxenes of Lindsley (1983), Figure 4. Note that the three-phase assemblage Opx-Aug-Pgt moves to more Fe-rich bulk compositions with decreasing temperature. Thus, matching the inferred compositions of the pyroxenes in the primary assemblages, particularly those involving Pgt, with the isothermal sections in Figure 4 allows the temperature corresponding to peak metamorphic conditions to be estimated. In fact each of the three textures described above and their inferred primary assemblages provide a constraint on the peak metamorphic temperature.

Assemblages derived from primary Opx-Cpx in the more Mg-rich rocks provide an absolute maximum temperature for metamorphism because they provide a compositional bound on the position of the three-phase field Opx-Aug-Pgt in the quadrilateral at peak conditions (Fig. 5). The position of this compositional bound is provided by the most Fe-rich samples with primary Opx-Aug, i.e., R25812. In this rock there is a considerable difference in X_{Fe} between host Opx and Opx lamellae in Aug. Thus, Fe-Mg exchange during cooling had ceased by the time the Opx lamellae had achieved their present form. The tie line

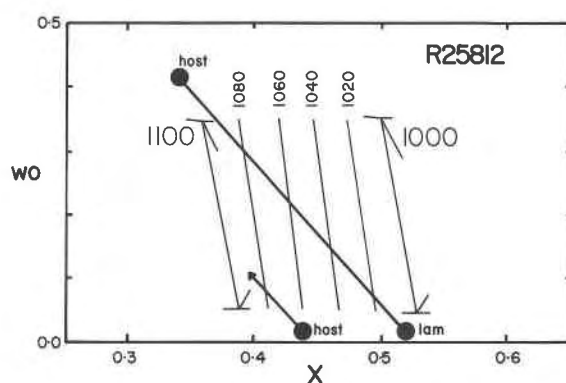


Fig. 5. Phase relations for pyroxenes in the more Mg-rich rocks exemplified by R25812. Thinner lines are positions of Opx-Aug boundary of the Opx-Aug-Pgt tie triangle for indicated temperatures. The analyzed hosts and lamellae are shown. See text for discussion.

between the Aug host and the Opx lamellae is much shallower than the high-temperature tie lines determined experimentally by Lindsley (1983), indicating substantial host-lamellae Fe-Mg equilibration during cooling. Given the small proportion of Opx lamellae in Aug and the smaller proportion of Aug lamellae in Opx, integrated pyroxenes will not be displaced far along the plotted tie lines. The anticlockwise rotation of the tie lines caused by the higher-temperature intercrystalline Fe-Mg re-equilibration can be undone qualitatively if the bulk composition about which the tie lines rotated is known. As this composition is unknown, although Aug predominates modally, this rock provides an upper temperature limit of about 1100°C if the bulk composition approached that of the Aug or a limit of 1060°C if it approached that of the Opx.

In the rocks of intermediate composition, the blebby intergrowths are believed to be derived from the breakdown of Pgt that formed part of the three-phase assemblage, or formed at compositions only slightly more Fe-rich than the three-phase assemblage, in the Pgt-Aug or Pgt-Opx field. Consequently, the composition of the Pgt provides an excellent constraint on the position of the three-phase assemblage at peak conditions. The composition of the bulk blebby intergrowth that has a proportion of Aug to Opx of 1:3.7 should correspond to the composition of the primary Pgt. Graphical reconstruction yields a Pgt composition $X_{Fe}^{Pgt} = 0.53$ for both R25547 and R25348B (Fig. 6). At peak conditions, this Pgt could have been stable with Opx ($X_{Fe}^{Opx} = 0.50$) or Aug ($X_{Fe}^{Aug} = 0.48$) or both. For the three-phase assemblage Pgt-Opx-Aug, a peak temperature of 1020°C is implied. Higher temperatures are implied if the Pgt was originally part of either of the two-phase assemblages Opx-Pgt or Pgt-Aug. Support for the interpretation that the blebby intergrowths originally formed part of the three-phase assemblage Pgt-Opx-Aug is provided by the observation that in the two samples in which it occurs, the pyroxene compositions are nearly identical.

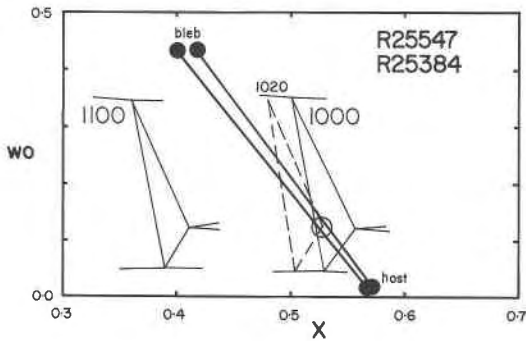


Fig. 6. Phase relations for pyroxenes in intermediate composition rocks. The dashed tie triangle, for the limiting case of Pgt bulk composition (open circle) in these rocks, gives a minimum temperature of 1020°C for the formation of the pyroxenes in these rocks. See text for discussion.

In the more Fe-rich rocks the primary pyroxene assemblages involved crystallization in the Aug-Pgt or Opx-Pgt fields, or as a single subcalcic Aug. The pyroxenes in these rocks provide a lower temperature limit because they provide a compositional bound on the position of the three-phase field Opx-Pgt-Aug, in analogous fashion to the Mg-rich assemblages. Moreover, the inferred subcalcic nature of some of the primary Aug provides some independent evidence of extremely high temperatures. Here the lower temperature limit is provided by the most Fe-rich pyroxenes. Granule exsolution is a problem (Bohlen and Essene, 1978); R25699 is preferred to R25390 for providing this limit because there is good textural control for this rock (Fig. 2), and granule exsolution is not suggested. The primary pyroxene in R25699 was a subcalcic Aug, now coarsely exsolved, making analytical reintegration difficult. In this case, reintegration was achieved by combining the compositions of the analyzed Aug and Opx lamellae in proportions appropriate to their areas. This somewhat hazardous procedure gives an approximate composition $Wo_{0.32}Fs_{0.37}En_{0.31}$. This composition provides a minimum temperature of 980°C, because the primary three-phase field Aug-Pgt-Opx must have existed at more Mg-rich compositions (Fig. 7). Higher temperatures, well in excess of 1000°C, are suggested by the subcalcic nature of the reintegrated Aug composition, although the actual temperature cannot be estimated because it is strongly dependent on the Wo content of the primary pyroxene, which is sensitive to small errors in reintegration.

In summary, the pyroxene-exsolution textures and compositional data combined with Lindsley's (1983) experimental data suggest that metamorphic temperatures at Fyfe Hills were in the vicinity of 1000°C. A preferred temperature of 1020°C is indicated by our interpretation of the origin of blebby intergrowths in rocks of intermediate composition and is supported by the upper and lower bound constraints imposed by the textural and compositional data in both more Mg- and more Fe-rich assemblages.

DISCUSSION

The exsolution textures in supracrustal pyroxene granulites from Enderby Land are indicative of exceptionally high metamorphic temperatures. Indeed, the temperatures suggested by the pyroxene granulites are significantly higher than temperatures deduced from more conventional geothermometry. Support for these exceedingly high temperatures is provided by the occurrence of various unusual mineral assemblages in metapelites from the Napier Complex including Mg-rich sapphirine (Spr) + quartz ($X_{Fe}^{Spr} = 0.19-0.25$), Ca-rich mesoperthite ($Or_{23}Ab_{60}An_{17}$), and Mg-rich osumulite (Osu) + quartz ($X_{Fe}^{Osu} = 0.03-0.21$) (Ellis et al., 1980; Grew, 1980, 1982; Sandiford, 1985a). The disparity between temperatures deduced from the pyroxene-exsolution textures (>1000°C) and the conventional two-pyroxene thermometers provides additional evidence that extreme caution must be employed when using conventional thermometry to deduce peak temperatures in high-temperature, slowly cooled metamorphic rocks (see also Essene, 1982).

Although the Enderby Land granulites represent an exceptionally high temperature metamorphism, they are not unique. Similar pyroxene textures have been recorded from granulites in the Scourian of Scotland (Barnicoat and O'Hara, 1979), and similar metapelitic assemblages have been recorded from a number of terranes including Wilson Lake, Labrador (Morse and Talley, 1971), and Labwor Hills, Uganda (Nixon et al., 1973). The similarity in assemblages suggests that all these terranes may have formed at temperatures close to or in excess of 1000°C. Such high temperatures are significant because they represent very substantial departures from the equilibrium crustal geotherm. Steady-state lower-crustal temperatures in modern shields are generally estimated to be in the range 400–500°C (Turcotte and Schubert, 1982). That such perturbations resulting in lower-crustal metamorphism of supracrustal rocks at temperatures of 1000°C may be rather more common than indicated by their current representation at the Earth's surface is suggested by the post-

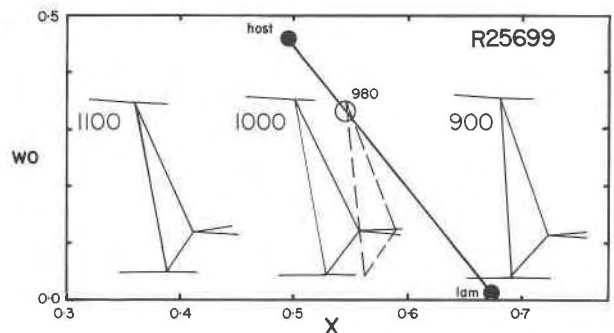


Fig. 7. Phase relations for the more Fe-rich rocks exemplified by R25699. The estimate of the original bulk composition and the compositions of Aug and Opx lamellae are shown. Dashed Opx-Aug-Pgt triangle is for the temperature at which Pgt breaks down for this bulk composition. See text for discussion.

metamorphic peak pressure-temperature-time paths of the exceptionally high temperature terranes in Enderby Land, Labwor Hills, and Wilson Lake, which show isobaric cooling (Ellis, 1980; Sandiford, 1985a). This implies that these terranes continued to reside near the bottom of the continental crust for long periods after metamorphism. The subsequent exposure of these terranes at the surface of the Earth is due to unrelated tectonic thickening of the crust occurring much later than the thermal perturbation. In the case of the Enderby Land granulites, near-surface emplacement occurred in late Proterozoic time some 1.0–1.5 Ga after granulite metamorphism (Sandiford, 1985b). Thus, many terranes metamorphosed at exceedingly high temperatures may still reside near the base of modern-day continental crust.

How are such extreme perturbations of continental geotherms generated? Because of the inferred formation of the high-temperature terranes near the base of the crust, abnormal heat flow from the mantle is implied. Whether the abnormal heat flow was produced by accretion of mantle-derived magmas, or was related to a dramatic thinning of the continental lithosphere, is unknown, although there is some evidence that metamorphism at Fyfe Hills was broadly contemporaneous with the emplacement of sill-like basic igneous bodies (Sandiford and Wilson, 1986). An observation that does not discriminate between mechanisms of heat supply but that is important with respect to the consequences of the high temperatures is that there appears to be no significant temperature gradient across the highest-temperature part of the Napier Complex despite pressure variations in excess of 2 kbar. The implication is that the dT/dP was very small. One explanation for this is that the temperature was buffered via the enthalpy of melting and, particularly, the loss of granitic melts upward. In Enderby Land this is supported by the dry residual character of the granulites (Sandiford and Wilson, 1986).

In light of this possibility it is interesting to note that the metamorphic temperatures in Enderby Land closely approach those required for dry melting of quartz + alkali feldspar (1050–1100°C, Huang and Wyllie, 1975). We would propose that this melting reaction provides an important constraint on the maximum temperature for the preservation of residual supracrustal granulites during crustal metamorphism. It suggests that the peak metamorphic temperatures at Fyfe Hills were not governed by the heat supply, but rather by an internal thermal buffering process. Whatever the nature of heat supply from the mantle, it must have been efficient and must have provided a considerable amount of heat to the lower crust.

ACKNOWLEDGMENTS

The Antarctic Division of the Department of Science is thanked for the opportunity to collect these rocks during the 1979–1980 Australian Antarctic Research Expedition. D. H. Lindsley and S. Bohlen are thanked for critically reviewing an earlier version of the manuscript.

REFERENCES

- Barnicoat, A.C., and O'Hara, M.J. (1979) High temperature pyroxenes from ironstone at Scourie, Sutherland. *Mineralogical Magazine*, 43, 371–375.
- Black, L.P., James, P.R., and Harley, S.L. (1983) Geochronology and structure of the early Archaean rocks at Fyfe Hills, Enderby Land, Antarctica. *Precambrian Research*, 21, 197–222.
- Bohlen, S.R., and Essene, E.J. (1978) Igneous pyroxenes from metamorphic anorthosite massifs. *Contributions to Mineralogy and Petrology*, 65, 433.
- Ellis, D.J. (1980) Osumilite-sapphirine-quartz granulites from Enderby Land, Antarctica: *P-T* conditions of metamorphism, implications for garnet-cordierite equilibria and the evolution of the deep crust. *Contributions to Mineralogy and Petrology*, 74, 201–210.
- Ellis, D.J., Sheraton, J.W., England, R.N., and Dallwitz, W.B. (1980) Osumilite-sapphirine-quartz granulites from Enderby Land, Antarctica—Mineral assemblages and reactions. *Contributions to Mineralogy and Petrology*, 72, 123–143.
- Essene, E.I. (1982) Geological thermometry and barometry. In J.M. Ferry, Ed. *Characterization of metamorphism through mineral equilibrium. Reviews in Mineralogy*, 10, 153–206.
- Ferguson, A.K., and Sewell, D.K.B. (1980) A peak integration method for acquiring X-ray data for on-line microprobe data. *X-ray Spectrometry*, 9, 48–51.
- Grew, E.S. (1980) Sapphirine-quartz association from the Archaean rocks of Enderby Land, Antarctica. *American Mineralogist*, 65, 821–836.
- (1982) Osumilite in the sapphirine-quartz-terrane of Enderby Land, East Antarctica: Implications for osumilite petrogenesis in the granulite facies. *American Mineralogist*, 67, 762–787.
- Huang, W.L., and Wyllie, P.J. (1975) Melting relations in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2$ to 35 kbars, dry and with excess water. *Journal of Geology*, 83, 737–748.
- Ishii, T., and Takeda, H. (1974) Inversion, decomposition and exsolution phenomena of terrestrial and extraterrestrial pigeonites. *Memoirs of the Geological Society of Japan*, 11, 19–36.
- Lindsley, D.H. (1983) Pyroxene thermometry. *American Mineralogist*, 68, 477–493.
- Morse, S.A., and Talley, J.H. (1971) Sapphirine reactions in deep-seated granulites near Wilson Lake, central Labrador, Canada. *Earth and Planetary Science Letters*, 10, 325–328.
- Newton, R.C. (1972) An experimental determination of the high pressure stability limits of cordierite under wet and dry conditions. *Journal of Geology*, 80, 398–420.
- Newton, R.C., and Haselton, H.T. (1981) Thermodynamics of garnet-plagioclase- AlSi_2O_5 -quartz geobarometer. In R.C. Newton, A. Navrotsky, and B.J. Wood, Eds. *Thermodynamics of minerals and melts*, 31–147. Springer-Verlag, New York.
- Newton, R.C., and Perkins, D. (1982) Thermodynamic calibration of geobarometers based on the assemblage garnet-plagioclase-orthopyroxene (clinopyroxene)-quartz. *American Mineralogist*, 67, 203–222.
- Newton, R.C., Charlu, T.V., and Kleppa, O.J. (1974) A calorimetric investigation of the high-pressure stability of anhydrous magnesium cordierite with application to granulite facies metamorphism. *Contributions to Mineralogy and Petrology*, 44, 295–311.
- Nixon, P.H., Reedman, A.J., and Burns, L.K. (1973) Sapphirine-bearing granulites from Lubwar, Uganda. *Mineralogical Magazine*, 39, 420–428.
- Powell, R. (1985) Geothermometry and geobarometry: A discussion. *Journal of the Geological Society of London*, 142, 29–38.
- Robinson, Peter. (1980) The composition space of terrestrial pyroxenes—Internal and external limits. In C.T. Prewitt, Ed. *Pyroxenes. Reviews in Mineralogy*, 7, 419–494.
- Robinson, Peter, Jaffe, H.W., Ross, M., and Klein, C., Jr. (1971)

- Orientation of exsolution lamellae in clinopyroxenes and clin amphiboles: Considerations of optimal phase boundaries. *American Mineralogist*, 56, 909–939.
- Sandiford, M. (1985a) The metamorphic evolution of granulites at Fyfe Hills; implications for Archaean crustal thickness in Enderby Land, Antarctica. *Journal of Metamorphic Geology*, 3, 155–178.
- (1985b) The origin of retrograde shear zones in the Napier Complex: Implications for the tectonic evolution of Enderby Land, Antarctica. *Journal of Structural Geology*, 7, 477–488.
- Sandiford, M., and Wilson, C.J.L. (1984) The structural evolution of the Fyfe Hills–Khmara Bay region, Enderby Land, East Antarctica. *Australian Journal of Earth Sciences*, 31, 403–426.
- (1986) The origin of Archaean gneisses in the Fyfe Hills region, Enderby Land: Field occurrence, petrography and geochemistry. *Precambrian Research*, 31, 37–68.
- Sheraton, J.W., and Black, L.P. (1983) Geochemistry of Precambrian gneisses: Relevance for the evolution of the East Antarctic Shield. *Lithos*, 16, 273–296.
- Sheraton, J.W., Offe, L.A., Tingey, R.J., and Ellis, D.J. (1980) Enderby Land, Antarctica—An unusual Precambrian high grade terrain. *Geological Society of Australia Journal*, 27, 1–18.
- Turcotte, D.L., and Schubert, G. (1982) *Geodynamics*. Wiley, New York, 450 p.
- Wells, P.R.A. (1977) Pyroxene thermometry in simple and complex systems. *Contributions to Mineralogy and Petrology*, 62, 129–139.

MANUSCRIPT RECEIVED OCTOBER 23, 1984

MANUSCRIPT ACCEPTED MARCH 18, 1986