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

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INTRODUCTION
In a discussion of our paper "Pyroxene exsolution in granulites from Fyfe Hills, Enderby Land, Antarctica: Evidence for 1000 °C metamorphic temperatures in Archean continental crust," Rietmeijer (1988) has concluded that the interpretations presented are "inconclusive and flimsy." In particular, Rietmeijer (1988) has argued that the critical pyroxene-exsolution temperatures in the Fyfe Hills granulites developed during cooling of magnetically crystallized pyroxenes, rather than cooling of metamorphic pyroxenes. By implication, Rietmeijer (1988) has suggested that we have failed to demonstrate the existence of any metapelitic (or indeed any metasedimentary) assemblages consistent with a 1000 °C metamorphic temperature. In response to Rietmeijer's (1988) discussion and in defense of the conclusions presented in our earlier paper, we take this opportunity to reiterate some critical points, namely, (1) the critical pyroxene-bearing assemblages described in Sandiford and Powell (1986a) occur in metasedimentary rocks (meta-ironstones) and therefore cannot be igneous in origin, and (2) the metapelites in the Enderby Land granulites contain a number of exceptionally rare assemblages consistent with regional metamorphism at temperatures at least as high as 1000 °C.

METSASEDIMENTARY IRONSTONES
Meta-ironstones consisting predominantly of magnetite and quartz with subordinate pyroxene occur throughout the Napier Complex in Enderby Land, where they typically occur as horizons less than 3 m thick associated with aluminous metasedimentary rocks (Sheraton et al., 1980; Grew, 1982a; Sandiford and Wilson, 1986; Harley, 1987). Complex exsolution textures indicative of the former presence of pigeonite have been documented from Mount Gleadell (Grew, 1982a), Fyfe Hills (Sandiford, 1985; Sandiford and Powell, 1986a), Tonagh Island (Harley, 1987), and Mount Riiser-Larsen (Grew, pers. comm., 1987). Whole-rock analyses of ironstones from Fyfe Hills show that SiO₂, FeO, and Fe₂O₃ typically total greater than 90 wt% (DePaolo et al., 1982; Sandiford and Wilson, 1986; see Table 1 in Sandiford and Powell, 1986a). MnO varies from minor amounts (<0.1 wt%) to greater than 16 wt% (Sandiford and Wilson, 1986) with the most Mn-

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if not unique, nature of the Enderby Land granulites, as witnessed by the occurrence on a regional scale of the following parageneses in metapelites: sapphirine + garnet + quartz + rutile, osmulite + sapphirine + quartz + rutile, sapphire + quartz + rutile, garnet + sapphire + quartz + rutile, and spinel + quartz (Sheraton et al., 1980; Ellis et al., 1980; Grew, 1980, 1982a; Sandiford, 1985; Harley, 1985, 1986; Fig. 1). At Fyfe Hills the following prograde assemblages have been documented in metapelites (all assemblages include mesoperthite or plagioclase, Sandiford, 1985): hypersthene + sillimanite + quartz + rutile + ilmenite, hypersthene + sapphirine + garnet + quartz + rutile + ilmenite, and sapphirine + sillimanite + garnet + quartz. Osmulite defines the nonterminal stability limit of K-feldspar in pelitic assemblages at temperatures in excess of 900–1000 °C at intermediate pressures (Ellis et al., 1980; Grew, 1982a). Its rarity in the geologic record testifies to the exceptional nature of the conditions required to stabilize osmulite, which has only been documented from a small number of high-temperature metamorphic terranes in addition to the Napier Complex (Berg and Wheeler, 1976; Bogdanova et al., 1980; Majer et al., 1977). With the exception of Enderby Land, metamorphic osmulite is restricted to very narrow “contact” aureoles adjacent to intrusive anorthosites. In Enderby Land, where intrusive anorthosites are unknown, osmulite occurs over some 4000 km², and a formerly much greater distribution is suggested by the occurrence of the characteristic cordierite + hypersthene + K-feldspar symplectitic breakdown products of osmulite over a further 6000 km² (Fig. 1; Sheraton et al., 1980; Grew, 1982a; Harley, 1985).

Enderby Land provided the first documented occurrence of the high-temperature association of sapphirine and quartz (Dallwitz, 1968), where it is now recorded over an area of at least 8000 km² (Fig. 1). Sapphirine + quartz assemblages have since been reported from at least five other granulite terranes (Nixon et al., 1973; Morse and Talley, 1971; Caporuscio and Morse, 1978; Grew, 1982b; Arima et al., 1986) where it is restricted to more oxidized assemblages along with ilmenohematite and/or magnetite. In contrast, either rutile or rutile and ilmenite are the stable Fe-Ti oxide(s) in the sapphirine + quartz assemblages of the comparatively reduced Napier Complex.

Variations in $a_{\text{H}_2\text{O}}$ have a profound effect on the topology of the systems FeO-MgO-Al$_2$O$_3$-Si$_2$O$_7$ (FMASO) and
Fig. 2. Petrogenetic grids for the system FeO-MgO-Al_2O_3-SiO_2-TiO_2-O_2 involving the phases cordierite = cd, sapphireine = sa, hypersthene, spinel = sp, garnet = g, sillimanite = sil, quartz, magnetite, hematite-ilmenite, and rutile. For clarity we have only considered assemblages with two Fe-Ti oxides, hypersthene, and quartz (see Powell and Sandiford, 1988). Two iso-a_02 grids are shown, for a_02 appropriate to ilmenite-rutile stability (in which the stable intersections are [sp] and [sil]) and for a_02 appropriate to ilmenohematite-magnetite stability (in which the stable intersections are [g], [sa], and [cd]), (see Hensen, 1986; Sandiford et al., 1987; Powell and Sandiford, 1988). The inversion point between the two topologies has been located assuming the Fe^{3+}/Fe^{2+} ratio of spinel is greater than that coexisting sapphireine (see Powell and Sandiford, 1988). The trace of the intersections with increasing a_02 occurs along the metastable extensions of the Fe-Ti oxide-absent univariants (shown as dashed lines). The invariant points [sp] and [sil] have been experimentally determined at 1030 °C and 1130 °C, respectively (Hensen and Green, 1973), whereas [g] may exist at temperatures in excess of 1000 °C (Annerstein and Seifert, 1981). The lower stability limit for the sapphireine-quartz association is shown for low a_02 and high a_02 by the light and heavy stiples, respectively. The unlabeled reactions are (1) spinel + cordierite = sillimanite and (2) spinel + sapphireine = sillimanite.

FMASO-TiO_2 (FMASO-TiO_2), which at high temperatures include the sapphireine + quartz association (Hensen, 1986; Sandiford et al., 1987; Powell and Sandiford, 1988). A topological inversion in these systems occurs at a_02 between the quartz + fayalite + magnetite and hematite + magnetite buffers (Fig. 2). With increasing a_02, the stability fields of sapphireine + quartz and spinel + quartz expand with respect to the lower-temperature, less-oxidized garnet-, cordierite-, and sillimanite-bearing assemblages. The pressure-temperature effects of changing a_02 on the stability of the sapphireine + quartz association are constrained according to the experimental results of Hensen and Green (1973) and Annerstein and Seifert (1981).

In experiments on model pelite compositions at a_02 lower than the quartz + fayalite + magnetite buffer, Hensen and Green (1973) located the spinel-absent invariant point [sp], which defines approximately the low-temperature stability limit of sapphireine + quartz, at temperatures in excess of 1030 °C (Fig. 2). Annerstein and Seifert (1981) intersected the (sapphireine + garnet)-absent univariant at a pressure of 9 kbar at 1000 °C at a_02 defined by the hematite + magnetite buffer over a range of Fe^{3+}/Fe^{2+} + Mg values, implying that even under these oxidized conditions, the sapphireine + quartz stability field is restricted to temperatures in excess of 1000 °C (Fig. 2). Harley (1986) has shown that the appropriate FMASO topology for the Enderby Land sapphireine + quartz assemblages is the low a_02 topology depicted in Figure 2. In the Fyfe Hills region the sapphireine + quartz + rutile + ilmenite assemblages are interlayered with prograde sillimanite + hypersthene + quartz + rutile + ilmenite assemblages. This implies that the peak temperatures were near the minimum required for the occurrence of sapphireine + quartz at a_02 appropriate to the stability of rutile and ilmenite (Fig. 2; garnet + sapphireine + quartz assemblages are stabilized in the Fyfe Hills region by the additional component CaO, Sandiford, 1985). Our preferred metamorphic-temperature estimate of 1020 °C based on pyroxene-exsolution textures (Sandiford and Powell, 1986a) is in excellent agreement with Hensen and Green (1973) experimental results for the stability of sapphireine + quartz and sillimanite + hypersthene at a_02 governed by the rutile + ilmenite buffer at a_02.

Finally, the extremely calcic nature of mesoperthite in metapelitic assemblages in Enderby Land is worthy of mention. The highest documented anorthite content for
Napier Complex mesoperthites in metapelites is An$_{23}$ (Sheraton et al., 1980), and at Fyfe Hills, metapelitic mesoperthites are commonly in the range An$_{19-17}$ (Sandiford, 1985). Such extreme compositions are consistent with the independent evidence for 1000 °C regional metamorphism in Enderby Land.

**DISCUSSION**

The occurrence of the critical pyroxene-exsolution textures in metasedimentary ironstones as well as the unusual metapelitic assemblages described briefly above and in more detail elsewhere (Ellis et al., 1980; Grew, 1982a; Sandiford, 1985; Harley, 1986) strongly supports the notion that a large portion of the Enderby Land granulite terrane (>8000 km$^2$) was metamorphosed at temperatures in the vicinity of 1000 °C. Although such temperatures are extreme, we see no reason in principle why crustal metamorphism should not occur at these temperatures. An important observation to be made from our Enderby Land studies is that the very extensive chemical re-equilibration attendant upon retrograde cooling effectively precludes the elucidation of prograde temperature maxima using conventional thermometric techniques. Only by using textural criteria to reconstruct prograde assemblages, such as outlined in Sandiford and Powell (1986a), is it possible to “see through” this retrograde cooling to the metamorphic "peak." Having done so, we suggest that the fundamental problem raised by our studies of the Enderby Land granulites is not whether regional metamorphism proceeds at temperatures as high as 1000 °C, but rather how temperatures of 1000 °C are generated in regional metamorphic terranes on the scale observed in Enderby Land. An intriguing insight into this problem is provided by the evidence that this 1000 °C temperature metamorphism occurred, or at the very least terminated, in crust of normal to subnormal thickness immediately following an episode of intense recumbent deformation (Sandiford, 1985; Sandiford and Powell, 1986b).

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