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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 we 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 magmatically 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.

METASEDIMENTARY 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 SiO_2, FeO, and Fe_2O_3 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-rich ironstones at Fyfe Hills containing sufficient BaO to stabilize hyalophane (Sandiford and Wilson, 1986). There appears little doubt that these ironstones are metasedimentary rocks with compositions akin to typical Precambrian banded iron formations (see also Sheraton et al., 1980; DePaolo et al., 1982; Grew, 1982a; Harley, 1987). It is indeed difficult to understand how such bulk compositions, particularly the Ba-Mn–rich ironstones, could derive from igneous processes where the rocks in question are interlayered with aluminous (garnet-sillimanite–bearing and/or sapphirine-bearing) metasedimentary rocks.

Sandiford and Powell (1986a, Tables 2 and 3) provided microprobe analyses for eleven pyroxene-bearing assemblages. Samples R25390, R25393, R31031, R25384, R25699, and R25693 are Mn-poor meta-ironstones as described above. In two of these, samples R25390 and R25699, pyroxenes occur in clustered aggregates within a matrix of magnetite and quartz, whereas in the other samples, pyroxenes occur as discrete grains (discounting the effects of exsolution) within the magnetite-quartz matrix (Fig. 2 in Sandiford and Powell, 1986a). The remaining five pyroxene-bearing assemblages described by Sandiford and Powell (1986a) have igneous (basaltic and pyroxenitic) bulk compositions.

The phase relationships deduced *from the six meta-ironstones* suggest that the three-phase assemblage pigeonite-orthopyroxene-augite occurred at $[Fe^{2+}/(Fe^{2+} + Mg)]$ Pgt = 0.58, implying a minimum equilibration temperature of 980 °C at 9 kbar using Lindsley's (1983) experimental results (Sandiford and Powell, 1986a). We interpret this to be a metamorphic temperature principally because the host rocks are metasedimentary. It is conceivable that the exsolution textures in the remaining five meta-igneous gneisses are relict igneous textures, as suggested by Rietmeijer (1988). However, the equilibration temperatures demanded by the pyroxenes in these meta-igneous gneisses do not differ significantly from those in the meta-ironstones. We see no problem in having all the pyroxene exsolution textures as the result of cooling following a metamorphic equilibration at temperatures of approximately 1000 °C.

METAPELITIC ASSEMBLAGES

In this section we wish to re-emphasize the wealth of petrologic data that have emerged from studies in Enderby Land in recent years concerning the exceptional,

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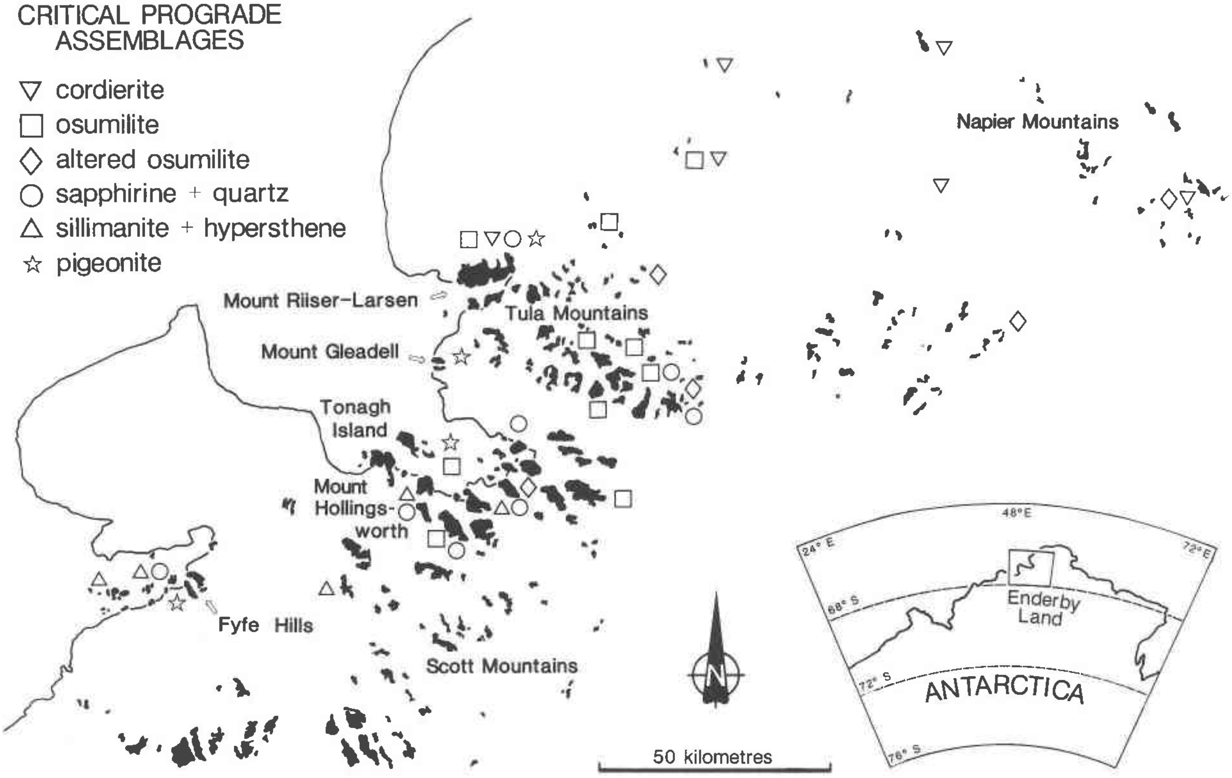

Fig. 1. Map showing the distribution of the critical mineral assemblages in the western and central Napier Complex, Enderby Land, Antarctica. The data sources are Sheraton et al. (1980), Ellis et al. (1980), Grew (1980, 1982a), Harley (1985, 1986), and Sandiford (1985). The boundaries of the Napier Complex are defined to the north by the Southern Ocean and to the south by the extent of regional late Proterozoic reworking (Sheraton et al., 1980), and thus the extent of Archean Napier Complex metamorphism may have been considerably greater than currently observed.

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, osumilite + sapphirine + quartz + rutile, sillimanite + hypersthene + quartz + rutile, garnet + sillimanite + 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. Osumulite 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 osumulite, 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; Maijer et al., 1977). With the exception of Enderby Land, metamorphic osumulite is restricted to very narrow "contact" aureoles adjacent to intrusive anorthosites. In Enderby Land, where intrusive anorthosites are unknown, osumulite occurs over some 4000 km^2, and a formerly much greater distribution is suggested by the occurrence of the characteristic cordierite + hypersthene + K-feldspar symplectitic breakdown products of osumulite over a further 6000 km^2 (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 km^2 (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 megnetite. 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_{O_2} have a profound effect on the topology of the systems $FeO-MgO-Al_2O_3-Si_2-O_2$ (FMASO) and

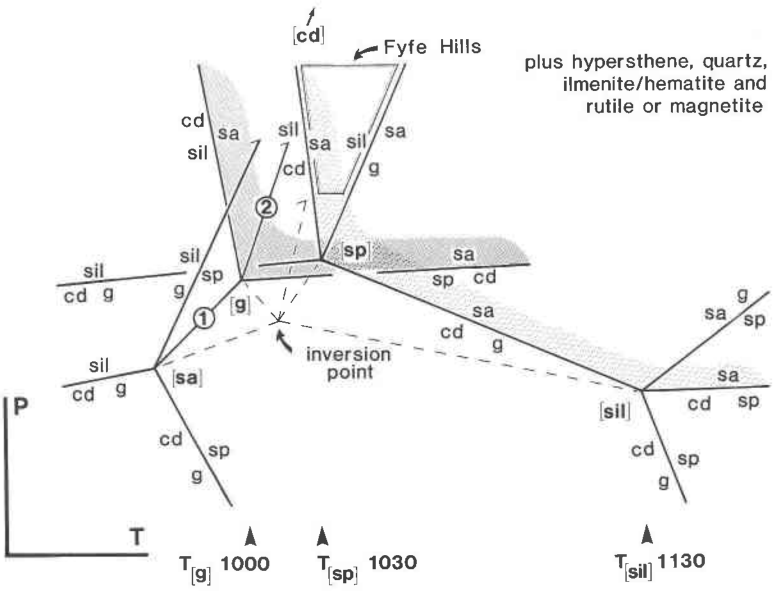

Fig. 2. Petrogenetic grids for the system FeO-MgO-Al_2O_3-SiO_2-TiO_2-O_2 involving the phases cordierite = cd, sapphirine = sa, hypersthene, spinel = sp, garnet = g, sillimanite = sil, quartz, magnetite, hematite-ilmenite, and rutile. For clarity we have only considered assemblages with two Fe-Ti oxides, hypersthene, and quartz (see Powell and Sandiford, 1988). Two iso-a_{O_2} grids are shown, for a_{O_2} appropriate to ilmenite-rutile stability (in which the stable intersections are [sp] and [sil]) and for a_{O_2} 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 sapphirine (see Powell and Sandiford, 1988). The trace of the intersections with increasing a_{O_2} 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 sapphirine-quartz association is shown for low a_{O_2} and high a_{O_2} by the light and heavy stiples, respectively. The unlabeled reactions are (1) spinel + cordierite = sillimanite and (2) spinel + sapphirine = sillimanite.

FMASO-TiO_2 (FMASTO), which at high temperatures include the sapphirine + quartz association (Hensen, 1986; Sandiford et al., 1987; Powell and Sandiford, 1988). A topological inversion in these systems occurs at a_{O_2} between the quartz + fayalite + magnetite and hematite + magnetite buffers (Fig. 2). With increasing a_{O_2}, the stability fields of sapphirine + 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_{O_2} on the stability of the sapphirine + 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_{O_2} 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 sapphirine + quartz, at temperatures in excess of 1030 °C (Fig. 2). Annerstein and Seifert (1981) intersected the (sapphirine + garnet)–absent univariant at a pressure of 9 kbar at 1000 °C at a_{O_2} defined by the hematite + magnetite buffer over a range of $Fe^{2+}/(Fe^{2+} + Mg)$ values, implying that even under these oxidized conditions, the sapphirine + 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 sapphirine + quartz assemblages is the low a_{O_2} topology depicted in Figure 2. In the Fyfe Hills region the sapphirine + 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 sapphirine + quartz at a_{O_2} appropriate to the stability of rutile and ilmenite (Fig. 2; garnet + sapphirine + 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's (1973) experimental results for the stability of sapphirine + quartz and sillimanite + hypersthene at a_{O_2} governed by the rutile + ilmenite buffer at a_{O_2}.

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_{10-17} (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 km²) 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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