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

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Metapelites in the Napier Complex granulites in Enderby Land (Antarctica) have well-documented parageneses supporting very high regional metamorphic temperatures (see references cited by Sandiford and Powell, 1986). Sandiford and Powell (1986) have claimed that pyroxene exsolution in these granulites provide evidence for 1000 °C metamorphic temperatures. Sandiford and Powell (1986) seemingly inferred a metamorphic origin for pyroxene-bearing rocks only from their occurrence within a regional metamorphic terrane, although they have provided no data on temporal relationships of the pyroxene-bearing rocks within the Fyfe Hills granulites. These temporal relationships can be critical to interpretations of metamorphic or igneous origins. For example, igneous rocks of different ages relative to the peak metamorphic event occur in the high-grade Precambrian granulite terrane of southwestern Norway (Hermans et al., 1975; Jansen et al., 1985; Rietmeijer, 1984). Furthermore, Sandiford and Powell (1986) have an unswerving conviction that temperatures derived from subsolidus and solvus pyroxene phase relations are uniquely metamorphic temperatures.

Before raising specific issues, I would like to recall a discussion by Miyashiro (1975) on concepts of metamorphism as a direct result of large-scale processes (i.e., regional metamorphism) and "small-scale metamorphism" such as changes within individual minerals. Although the latter type will provide valuable data on physico-chemical processes that occurred during the history of a given mineral grain, it does not necessarily reflect the overall regional metamorphic pattern. A case in point is that pyroxenes in meta-igneous rocks may show a record of crystallization and igneous cooling prior to coincidence with the surrounding regional metamorphic thermal regime (Rietmeijer, 1979, 1984).

By definition, exsolution occurs in solid solutions during cooling from the highest equilibration temperature reached by a solid solution. This equilibration temperature could be either a solidus (igneous) or subsolidus (metamorphic) temperature. Thus, pyroxene exsolution cannot a priori bracket peak regional metamorphic temperatures.

Pyroxene exsolutions described by Sandiford and Powell (1986) show a degree of complexity commonly observed in slowly cooled igneous pyroxenes (Robinson et al., 1977; Robinson, 1980; Rietmeijer, 1979; Rietmeijer and Champness, 1980, 1982; Ranson, 1986). In general, metamorphic pyroxenes have simple patterns of exsolution lamellae ∥ 100 and "001" ("*hkl*" denoting orientations approximately parallel to *hkl*; Jaffe et al., 1975).

It is conceivable that in unusually high-temperature metamorphic rocks, complex subsolidus phase relations in pigeonite (Pgt) and Ca-rich clinopyroxene (Aug) may arise in response to slow regional cooling. These patterns could be reminiscent of the complex subsolidus patterns for slowly cooled, igneous clinopyroxenes. However, a critical issue for the conclusions reached by Sandiford and Powell (1986) is the origin of the pyroxenes selected for their analyses.

For their claim of 1000 °C metamorphic temperatures derived from pyroxene exsolution, it has to be shown *beyond a shadow of doubt* that selected pyroxenes indeed have a metamorphic origin. Pyroxenes have been selected from basic and intermediate meta-igneous rocks of basaltic composition and ferruginous metasedimentary rocks for which representative whole-rock analyses are presented (Sandiford and Powell, 1986, Table 1). I suggest that bulk composition and occurrence within a granulite terrane alone are not sufficient to establish a metamorphic origin for a particular rock or mineral grain. Thus, without additional evidence in support of a metamorphic origin for the "more Mg-rich" and "intermediate composition" rocks, Sandiford and Powell (1986) have drawn a tenuous conclusion for their pyroxene origins. Indeed, the whole-rock composition and exsolutions of constituent pyroxenes in these rocks are consistent with an igneous origin.

Also, Sandiford and Powell (1986) compared pigeonite exsolutions in the Fyfe Hills granulites to decomposed pigeonites described by Ishii and Takeda (1974) from a coarse-grained basaltic dike. Ishii and Takeda (1974) were careful to note that formation of decomposed pigeonite is based on the assumption that the orthopyroxene (Opx)-Pgt-Aug three-phase assemblage will also occur in the crystallization process during subsolidus cooling, i.e., equilibrium occurs among these three pyroxenes. Surprisingly, Sandiford and Powell (1986) admitted that they have no evidence for the coexistence of the three primary phases. With the nonigneous nature of the selected pyroxenes inconclusively established, the 1020 °C temperature derived from the graphically reconstructed, decomposed pigeonite (Sandiford and Powell, 1986, Fig. 6) is not well-founded and may not reflect peak regional metamorphic conditions. In addition, the temperature esti-

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mate is presented without reference to the probable errors involved in graphical reconstructions of primary pyroxene compositions from their exsolutions (see below).

The ferruginous metasedimentary rocks may be candidates for metamorphic pyroxene assemblages that formed in response to peak-metamorphic temperatures producing the parageneses in metapelites from the Fyfe Hills granulites. However, within the context of the "exceedingly high temperatures" (Sandiford and Powell, 1986), it is not inconceivable to expect unusual compositions for igneous components within the granulites. Accepting a probable metamorphic origin for the "more Fe-rich rocks" (terminology after Sandiford and Powell, 1986), I note that (1) there is no evidence for the existence of the Opx-Pgt-Aug three-phase assemblage in these rocks and (2) compositions of primary subcalcic augite is obtained by the "somewhat hazardous procedure" (Sandiford and Powell, 1986) of graphical reconstruction. In general, graphical reconstruction for slowly cooled exsolved Ca-rich clinopyroxenes will overestimate the amount of Ca-poor pyroxene lamellae, and the resulting reconstructed primary augite will be too low in Ca (Rietmeijer, 1979). The errors involved in this procedure may be ±100 °C (Bohlen and Essene, 1978; Rietmeijer and Champness, 1982). Thus, the 980 °C temperature estimate derived from subcalcic augite is too uncertain to support the claim for exceptionally high metamorphic temperatures based on pyroxene exsolutions.

In conclusion, the evidence presented by Sandiford and Powell (1986) for 1000 °C metamorphic temperatures based on pyroxene exsolution in granulites from Fyfe Hills (Enderby Land, Antarctica) is inconclusive and flimsy.

Acknowledgments

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References cited

Bohlen, S.R., and Essene, E.J. (1978) Igneous pyroxenes from metamorphosed anorthosite massifs. Contributions to Mineralogy and Petrology, 65, 433–442.

Hermans, G.A.E.M., Tobi, A.C., Poorter, R.P.E., and Maijer, C. (1975) The high-grade metamorphic Precambrian of the Sirdal-Orsdal area, Rogaland/Vest-Agder, southwest Norway. Norges Geologiske Undersokelse, 318, 51–74.

Ishii, T., and Takeda, H. (1974) 3. Inversion, decomposition and exsolution phenomena of terrestrial and extraterrestrial pigeonites. Memoirs of the Geological Society of Japan, 11, 19–36.

Jaffe, H. W., Robinson, P., Tracy, R.J., and Ross, M. (1975) Orientation of pigeonite lamellae in metamorphic augite: Correlation with composition and calculated optimal phase boundaries. American Mineralogist, 60, 9–28.

Jansen, J.B.H., Blok, R.J.P., Bos, A., and Scheelings, M. (1985) Geothermometry and geobarometry in Rogaland and preliminary results from the Bamble area, south Norway. In A.C. Tobi and J.L.R. Touret, Eds., The deep Proterozoic crust in the North Atlantic provinces, p. 499–516. D. Reidel, Boston, Massachusetts.

Miyashiro, A. (1975) Metamorphism and metamorphic belts, 492 p. Allen and Unwin, London.

Ranson, W.A. (1986) Complex exsolution in inverted pigeonite: Exsolution mechanisms and temperatures of crystallization and exsolution. American Mineralogist, 71, 1322–1336.

Rietmeijer, F.J.M. (1979) Pyroxenes from iron-rich igneous rocks in Rogaland, SW Norway. Geologica Ultraiectina, 21, 341.

——— (1984) Pyroxene (re-) equilibration in the Precambrian terrain of SW Norway between 1030–990 Ma and reinterpretation of events during regional cooling (M3 stage). Norsk Geologisk Tidsskrift, 64, 7–20.

Rietmeijer, F.J.M., and Champness, P.E. (1980) Inverted pigeonites from Rogaland, SW Norway. Institute of Physics Conference Series, no. 52, 105–108.

——— (1982) Exsolution structures in calcic pyroxenes from the Bjerkreim-Sokndal lopolith, SW Norway. Mineralogical Magazine, 45, 11–24.

Robinson, P. (1980) The composition space of terrestrial pyroxenes—Internal and external limits. Mineralogical Society of America Reviews in Mineralogy, 7, 419–494.

Robinson, P., Ross, M., Nord, G.L., Jr., Smith, J.R., and Jaffe, H.W. (1977) Exsolution lamellae in augite and pigeonite: Fossil indicators of lattice parameters at high temperature and pressure. American Mineralogist, 62, 857–873.

Sandiford, M., and Powell, R. (1986) Pyroxene exsolution in granulites from Fyfe Hills, Enderby Land, Antarctica: Evidence for 1000 °C metamorphic temperatures in Archean continental crust. American Mineralogist, 71, 946–954.

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