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A recalibration of the garnet-olivine geothermometer and a new geobarometer for garnet peridotites and garnet-olivine-plagioclase-bearing granulites

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ABSTRACT The garnet-olivine Fe-Mg exchange geothermometer and the garnet-olivine-plagioclase geobarometer have been simultaneously calibrated using reversed experimental data based on the model reactions

$$3Fe_2SiO_4 + 2Mg_3Al_2Si_3O_{12} = 3Mg_2SiO_4 + 2Fe_3Al_2Si_3O_{12}$$

and

$$3Fe_2SiO_4 + 3CaAl_2Si_2O_8 = 2Fe_3Al_2Si_3O_{12} + Ca_3Al_2Si_3O_{12}$$

between 900 and 1500 °C at 9.1–95.0 kbar and between 4.7 and 7.0 kbar at 750–1050 °C, respectively. The resulting garnet-olivine thermometer reproduces experimental temperatures mostly within ±75 °C and the garnet-olivine-plagioclase barometer reproduces experimental pressures well within ±0.19 kbar. These new thermobarometers use the same garnet and olivine activity models and are thermodynamically consistent. Application of these thermobarometers to garnet peridotites from mantle xenoliths, orogenic garnet peridotites over the world and the Adirondack olivine-bearing metagabbros yielded reasonable *P–T* results. The present garnet-olivine thermometer can be used to measure medium-high-grade to ultrahigh-grade, low-pressure to ultrahigh–high-pressure garnet peridotites and metagabbros, whereas the garnet-olivine-plagioclase barometer has limited application to garnet-olivine-plagioclase-bearing granulites.

Key words: application; calibration; garnet; geobarometer; geothermometer; olivine; plagioclase assemblage.

INTRODUCTION

The stable assemblage garnet + olivine ± plagioclase may coexist in medium-high-temperature to ultrahigh-temperature, low-pressure to ultrahigh–high-pressure metamorphic rocks in the crust and possibly in the upper mantle, usually in garnet peridotites. Garnet peridotites usually occur at moderate depths in the upper mantle and are characteristic of mantle xenolith suites in kimberlites and basalts, and also occur in tectonically emplaced peridotite (± eclogite) terranes (Nickel & Green, 1985). The tectonically emplaced peridotites are usually termed 'orogenic peridotites' or 'peridotite massifs' or 'alpine-type peridotites' and typically occur within metamorphosed continental crustal rocks as lensoid masses (Beyer *et al.*, 2006), i.e. usually within high-pressure and ultrahigh-pressure metamorphic terranes in the root zones of orogenic belts probably formed due to continental collision (Brueckner & Medaris, 2000).

The relationship between the garnet peridotites and eclogites in these settings is not always straightforward, and reliable geothermobarometry together with detailed petrographical observations are very important to sort this out. Thus, a revised and apparently more accurate garnet-olivine Fe-Mg geothermometer is welcome. The assemblage garnet + olivine ± plagioclase, however, is probably restricted to mafic rocks equilibrated within a narrow pressure window at intermediate to high temperatures, and is expected to be very rare. Because in ultramafic rocks the assemblage garnet-olivine-plagioclase is not expected to appear, as plagioclase + olivine at low pressures will be succeeded by spinel + olivine before garnet + olivine becomes stable at even higher pressures. Thus the garnet-olivine-plagioclase barometer will be of marginal interest only, in contrast to the garnet-olivine thermometer (E. J. K. Ravna, personal communication).

The garnet–olivine Fe-Mg exchange geothermometer (Kawasaki & Matsui, 1977; O'Neill & Wood, 1979; Hackler & Wood, 1989; Brey *et al.*, 1990, 1999; Taylor, 1998; Frost, 2003) and the garnet-olivine-plagioclase geobarometer (Bohlen *et al.*, 1983;

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Perkins & Vielzeuf, 1992) have been experimentally calibrated and have been used to determine the P–T conditions of such rocks (e.g. Johnson & Essene, 1982; Gaul *et al.*, 2000; Menzies *et al.*, 2004). At present, however, these geothermometer and geobarometer are less accurate and are thermodynamically independent from each other, which limit their application. Here they are recalibrated as thermodynamically consistent thermobarometers through simultaneous treatment of the experimental data, and then, to test their applicability, the new thermometer and barometer have been applied to garnet peridotites from mantle xenoliths and collisional zones as well as the Adirondack olivine-bearing metagabbros. The results show that the new garnet-olivine geothermometer and the garnet-olivine-plagioclase geobarometer can be more specifically applied to assemblages containing coexisting garnet + olivine ± plagioclase.

THE GARNET-OLIVINE GEOTHERMOMETER

The Fe-Mg exchange reaction between garnet and olivine

$$\underset{\text{fayalite}}{3\,Fe_2SiO_4} + \underset{\text{pyrope}}{2Mg_3Al_2Si_3O_{12}} = \underset{\text{forsterite}}{3Mg_2SiO_4} + \underset{\text{almandine}}{2Fe_3Al_2Si_3O_{12}} \quad (1)$$

has been experimentally investigated by Kawasaki & Matsui (1977), O'Neill & Wood (1979), Hackler & Wood (1989), Brey *et al.* (1990), Taylor (1998), Brey *et al.* (1999) and Frost (2003). Kawasaki & Matsui (1977) conducted the Fe-Mg exchange experiments between garnet and olivine at 1100 °C and 50 kbar using synthetic binary Fe-Mg garnet and olivine. O'Neill & Wood (1979) reversed the Fe-Mg exchange equilibrium in the temperature range of 900–1400 °C at 30 kbar using synthetic binary Fe-Mg garnet and olivine and derived a garnet-olivine thermometer formalism (later corrected; see O'Neill, 1980), but unfortunately, they did not report the chemical compositions of the run product garnet and olivine. The Hackler & Wood (1989) experiments were conducted at 1000 °C and 9.1 kbar using synthetic binary Fe-Mg garnet and olivine. Final equilibrium garnet compositions range from 33.5 to 82.6 mol.% almandine, and olivine ranges from 25.5 to 81.0 mol.% fayalite. The Brey *et al.* (1990) experiments were performed at 900–1400 °C and 28–60 kbar, using six kinds of natural lherzolitic compositions as starting material. Brey & Köhler (1990) derived a new garnet-olivine thermometer based on their experimental data of quaternary garnet and binary olivine, assuming ideal mixing in both phases. The Taylor (1998) experiment was carried out at 1050–1260 °C and 20–35 kbar for magnesium-rich systems, resulting in the equilibrium quaternary garnet of 7–18 mol.% almandine and binary olivine with 4–14 mol.% fayalite. The experiments of Brey *et al.* (1999) used synthetic ternary Fe-Mg-Ca garnet and binary olivine and were reversed between 1200 and 1500 °C at 30–50 kbar. The Frost (2003) experiments were carried out at 1400°C and 9.5 and 13 GPa using synthetic binary and ternary garnet and binary olivine. In calibrating the garnet-olivine thermometer, all the experimental data mentioned above were used and are listed in Table S1.

It is well known that the Gibbs free energy of a reaction system at equilibrium is

$$\Delta G = 0 = \Delta G^0 + RT \ln K \quad (2)$$

in which K is the equilibrium constant and is expressed as the product of the activities of the phases. When choosing 1 bar and 298.15 K as the reference state, for each end-member mineral phase, the Gibbs free energy contribution to ΔG^0 is (Holland & Powell, 1990):

$$\Delta_f G = \Delta H^0_{(1,298.15)} - T\Delta S^0_{(1,298.15)} + \int_{298.15}^{T} C_p \, dT - T\int_{298.15}^{T} \frac{C_p}{T} \, dT + P[V^0_{(1,298.15)} + \alpha V(T - 298.15)] - \frac{\beta V}{2} P^2 \quad (3)$$

in which $\Delta H^0_{(1,298.15)}$ and $\Delta S^0_{(1,298.15)}$ are standard-state (1 bar, 298.15 K) enthalpy and entropy of the phase, respectively, and C_p, α and β are heat capacity, thermal expansion coefficient and compressibility coefficient of the phase, respectively. For geothermometry for solid-state phases, it is a common and reasonable practice to ignore C_p, α and β of the phases. Thus combining Eqs (2) and (3), the thermodynamical equilibrium of the Fe-Mg exchange reaction between garnet and olivine can be described as:

$$\Delta G = 0 = \Delta H^0 - T\Delta S^0 + P\Delta V^0 + RT \ln K_d + 6RT \ln\left(\frac{\gamma^{grt}_{Fe}}{\gamma^{grt}_{Mg}}\right) + 6RT \ln\left(\frac{\gamma^{ol}_{Mg}}{\gamma^{ol}_{Fe}}\right) \quad (4)$$

in which the delta items are the corresponding thermodynamic parameters of reaction (1), and the γ-related items are the activity coefficients of the corresponding phases. The molar volume change of reaction (1) used here is -0.406 J bar^{-1} (Holland & Powell, 1990).

There are currently three quaternary garnet solid-solution models (e.g. Berman, 1990; Ganguly *et al.*, 1996; Holdaway, 2001) derived from fitting the existing experimental data and/or natural data. The Holdaway (2001) model is the average of the three ternary or quaternary models (Berman, 1990; Ganguly *et al.*, 1996; Mukhopadhyay *et al.*, 1997). Through extensive comparative studies, Wu & Cheng (2006) concluded that the Holdaway (2000) garnet-biotite thermometer and the Holdaway (2001) GASP barometer are the most accurate and valid versions of

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these thermobarometers. Thus we prefer the Holdaway (2001) garnet model and the Fuhrman & Lindsley (1988) plagioclase activity model which are used in the GASP barometer.

Olivine may be described as a symmetric Fe-Mg binary solid solution, thus:

$$2RT \ln\left(\frac{\gamma^{ol}_{Mg}}{\gamma^{ol}_{Fe}}\right) = W^{ol}_{FeMg} \cdot 2(X^{ol}_{Fe} - X^{ol}_{Mg}) \quad (5)$$

Combining Eqs (4) and (5) and applying the Holdaway (2001) garnet activity model, a regression model of the garnet-olivine thermometer has been obtained as:

$$\begin{aligned} -\Delta H^0 + T\Delta S^0 - 6(X^{ol}_{Fe} - X^{ol}_{Mg})W^{ol}_{FeMg} &= -0.406P \\ + RT \ln K_d + 2(\mathrm{Fea} - \mathrm{Mga})T + 2(\mathrm{Feb} - \mathrm{Mgb})P \\ + 2(\mathrm{Fec} - \mathrm{Mgc}) \end{aligned} \quad (6)$$

in which the terms Fea, Feb, Fec, Mga, Mgb and Mgc are polynomials describing the activity coefficients of almandine and pyrope in garnet and these have been given in Table S2.

For chemical generality, the regression has been weighted. The numbers of the Fe-rich samples have been multiplied by a suitable factor so that the Fe-rich and Mg-rich samples in the regression are nearly equal in quantity. Regression of this thermometer model using the experimental data (Table S1) yielded $\Delta H^0 = -58136.3$ (± 2765.4) J mol^{-1}, $\Delta S^0 = -38.743$ (± 2.0) J K^{-1}mol^{-1} and $W^{ol}_{FeMg} = 3942.3$ (± 113.8) J mol^{-1}, with a multiple correlation coefficient $R = 0.909$. In the computation, 21 of the total 151 runs were discarded in order to improve the regression quality. These include runs 1371, 1331, 1311, 1421, 1341, 1080, 1311, 1382, 1302, 1392 and 1080 (Kawasaki & Matsui, 1977), and P21(Baro), 500(Baro), 463(Nor) and 347(Baro) (Brey *et al.*, 1990), and T2308 and T2614 (Taylor, 1998), and 789/6 and 72/3 (Brey *et al.*, 1999), and S2773B and H1556 (Frost, 2003). In fact, most of these discarded runs clearly deviate from the regression curves in Roozeboom diagrams. In our computation, all Fe in garnet and olivine were assumed to be ferrous.

Substituting the regressed parameters into the regression model (Eqn 6) yielded the garnet-olivine thermometer formalism as:

$$\begin{aligned} T(K) = (&58136.3 + P(\mathrm{bar})(0.406 - 2\mathrm{Feb} + 2\mathrm{Mgb}) \\ &- 2\mathrm{Fec} + 2\mathrm{Mgc} - 23653.8(X^{ol}_{Fe} - X^{ol}_{Mg})) \\ &/(38.743 + 2\mathrm{Fea} - 2\mathrm{Mga} \\ &+ 6R \ln[(X^{grt}_{Fe}/X^{grt}_{Mg})/(X^{ol}_{Fe}/X^{ol}_{Mg})]) \end{aligned} \quad (7)$$

This thermometer reproduces the experimental temperatures (Table S1) mostly within ± 75 °C (Fig. 1), and this formulation is much more precise than the thermometers of O'Neill & Wood (1979) and Brey & Köhler (1990) (Fig. 1).

THE GARNET-OLIVINE-PLAGIOCLASE GEOBAROMETER

The garnet-olivine-plagioclase equilibrium

$$\underset{\text{fayalite}}{3Fe_2SiO_4} + \underset{\text{anorthite}}{3CaAl_2Si_2O_8} = \underset{\text{almandine}}{2Fe_3Al_2Si_3O_{12}} + \underset{\text{grossular}}{Ca_3Al_2Si_3O_{12}} \quad (8)$$

has been experimentally determined by Bohlen *et al.* (1983) and later by Perkins & Vielzeuf (1992). Bohlen *et al.* (1983) tightly reversed the reaction curve in *P–T* space based on their seven brackets using synthetic pure fayalite and anorthite as well as synthetic impure garnet ($Gros_1Alm_2$) in the piston–cylinder apparatus under physical conditions of 750–1050 °C at 4.7–7.0 kbar. Perkins & Vielzeuf (1992) redetermined this barometer based on their four brackets using synthetic phases as that of Bohlen *et al.* (1983) in the piston–cylinder apparatus in the range of 900–1050 °C at 6.0–7.3 kbar. The experimental reversals of Perkins & Vielzeuf (1992) were less tightly reversed ($\pm$ 0.3 to 0.5 kbar) for a narrower *P–T* range and are several hundred bars higher than that of Bohlen *et al.* (1983) and the slope in *P–T* space is a little different from that of Bohlen *et al.* (1983). However, as Perkins & Vielzeuf (1992) stated, when considering errors in measuring the pressures of the experiments in the temperature range 900–1050 °C, their experiments are completely consistent with the experimental brackets of Bohlen *et al.* (1983). Thus in the regression we used the experimental midpoint data of the reversals of Bohlen *et al.* (1983) and the lower limit pressures of the experimental reversals of Perkins & Vielzeuf (1992), because these data (Table S3) are consistent.

For the barometer reaction (8), combining Eqs (3) and (2), the garnet-olivine-plagioclase barometer model has been obtained as

$$\begin{aligned} -\Delta H^0_{(1,298.15)} + T\Delta S^0_{(1,298.15)} &= \int_{298.15}^{T} \Delta C_p \, dT \\ - T\int_{298.15}^{T} \frac{\Delta C_p}{T} \, dT - \frac{\Delta(\beta V)}{2}P^2 + P[\Delta V^0_{(1,298.15)} \\ + \Delta(\alpha V)(T - 298.15)] + 6RT \ln \gamma^{grt}_{Fe} + 3RT \ln \gamma^{grt}_{Ca} \\ - 6RT \ln \gamma^{ol}_{Fe} - 3RT \ln \gamma^{pl}_{Ca} + RT \ln\left[\frac{(X^{grt}_{Fe})^6 (X^{grt}_{Ca})^3}{(X^{ol}_{Fe})^6 (X^{pl}_{Ca})^3}\right] \end{aligned} \quad (9)$$

The asymmetric quaternary garnet activity model of Holdaway (2001), along with the symmetric binary olivine activity model derived in this paper, together with the asymmetric ternary plagioclase activity model of Fuhrman & Lindsley (1988) were used in the calibration. Regressing Eqn (9) using the experimental data of Bohlen *et al.* (1983) and Perkins & Vielzeuf (1992) yielded $\Delta H^0 = -5796.9$ (± 2893.0) J mol^{-1} and $\Delta S^0 = -78.624$ (± 2.4) J K^{-1} mol^{-1}, with a multiple

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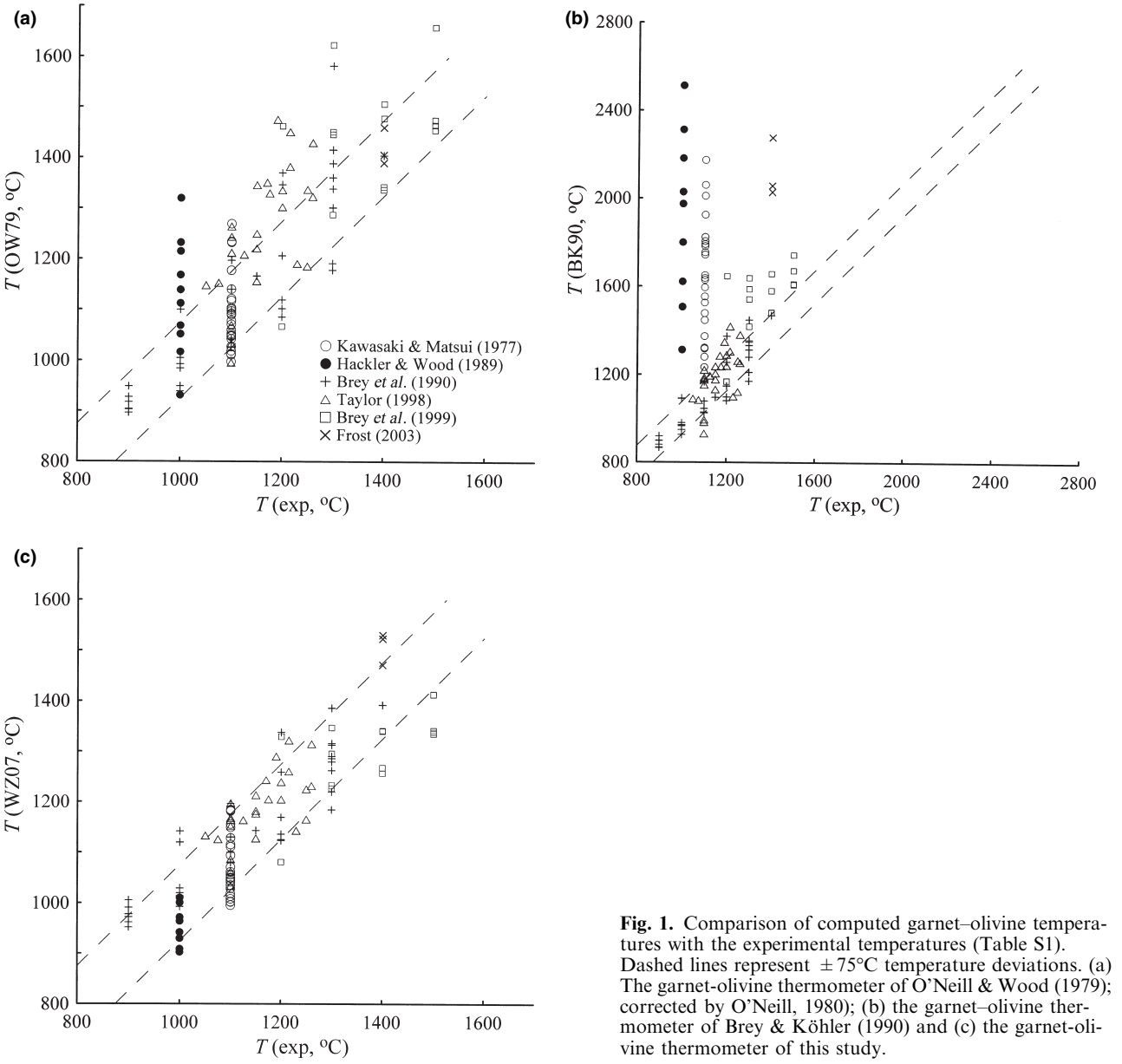


Fig. 1. Comparison of computed garnet–olivine temperatures with the experimental temperatures (Table S1). Dashed lines represent ±75°C temperature deviations. (a) The garnet-olivine thermometer of O'Neill & Wood (1979); corrected by O'Neill, 1980); (b) the garnet–olivine thermometer of Brey & Köhler (1990) and (c) the garnet-olivine thermometer of this study.

correlation coefficient $R = 0.996$. Substituting these regressed values into Eq. (9), yields the barometer formulation as

$$P\ (\text{bar}) = \Big\{ 397423.0 + 7270.124T(K) + 0.17703T^2 - 65805.2T^{0.5} - 9613750.0T^{-1} - 820.7T \ln T + T(2\text{Fea} + \text{Caa} - 3\text{Fa}) + P(2\text{Feb} + \text{Cab} - 3\text{Fb}) + (2\text{Fec} + \text{Cac} - 3\text{Fc}) + 1.495 \times 10^{-5}P^2 - 23653.8(X_{\text{Mg}}^{\text{ol}})^2 + RT \ln \left[\frac{(X_{\text{Fe}}^{\text{grt}})^6 (X_{\text{Ca}}^{\text{grt}})^3}{(X_{\text{Fe}}^{\text{ol}})^6 (X_{\text{Ca}}^{\text{pl}})^3} \right] \Big\} \div [8.57 - 1.4 \times 10^{-5}(T - 298.15)] \quad (10)$$

in which the terms Fa, Fb and Fc are polynomials describing the activity coefficients of anorthite in plagioclase (Fuhrman & Lindsley, 1988) and are given in Table S2. This formulation reproduces the experimental pressures of Bohlen *et al.* (1983) well within ±97 bar, and reproduces the lower limits of the experimental reversals of Perkins & Vielzeuf (1992)

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well within −3 to −187 bar. It should be stated that if the midpoints of the Perkins & Vielzeuf (1992) experimental reversals were included in the regression, poorer results would be obtained although the experimental pressures would be reproduced within ±0.32 kbar for both of the two sets of experiments.

Alternatively, if the garnet activity model of Berman (1990) is used, regression of the two experimental data sets yielded $H^0 = -7540.2$ (± 2884.6) J mol^{-1} and $\Delta S^0 = -79.788$ (± 2.4) J K^{-1}mol^{-1} with $R = 0.996$. Using the garnet activity model of Ganguly *et al.* (1996), regression of the two experimental data sets yielded $\Delta H^0 = -7707.0$ (± 2900.7) J mol^{-1} and $\Delta S^0 = -80.212$ (± 2.4) J K^{-1} mol^{-1} with $R = 0.996$. These two regressions produce identical pressures as that of the regression using Holdaway's (2001) garnet activity model, although the Holdaway (2001) model is preferred.

TEST OF THE GARNET-OLIVINE-PLAGIOCLASE GEOTHERMOBAROMETERS

To test the applicability of the present garnet-olivine thermometer, additional garnet peridotite data were collected and are listed in Table S4. These include: (i) garnet peridotites as mantle xenoliths from Siberia (Luth *et al.*, 1990; Ionov *et al.*, 1993; Ionov, 2004), South Africa (Shee *et al.*, 1982; Luth *et al.*, 1990; Saltzer *et al.*, 2001), Canada (Menzies *et al.*, 2004), Antarctica (Foley *et al.*, 2006), China (Jin & Pan, 1998) and Argentina (Bjerg *et al.*, 2005); and (ii) orogenic garnet peridotites from the Western Gneiss Region of Norway (Beyer *et al.*, 2006; Vrijmoed *et al.*, 2006), the UHP SuLu–Dabie Orogenic Belt of China (Yang *et al.*, 1993; Yang & Jahn, 2000; Zhang *et al.*, 2003), other orogenic belts of China (Yu *et al.*, 2001; Song *et al.*, 2004, 2007; Zhang *et al.*, 2005), the Alps (Medaris *et al.*, 1990; Nimis & Trommsdorff, 2001; Hermann *et al.*, 2006) and Indonesia (Kadarusman & Parkinson, 2000). As recommended by Brenker & Brey (1997), the preferred method for calculating peak *P–T* values for garnet peridotites is to apply the olivine-garnet thermometer coupled with the Al-in-orthopyroxene geobarometer, because Fe and Mg diffusion is relatively slow in garnet compared with that in olivine and pyroxene, Al diffusion is slow in orthopyroxene, and olivine, which is the predominant phase, will undergo the least compositional change during cooling (Medaris *et al.*, 2005). The *P–T* conditions of the garnet peridotites (Table S3) may be determined by simultaneously applying the garnet-orthopyroxene geothermometer and Al-in-orthopyroxene geobarometer (Harley, 1984a,b), clinopyroxene-orthopyroxene thermometer and Al-in-orthopyroxene geobarometer (Brey & Köhler, 1990), which were experimentally calibrated. It is noted that the Brey & Köhler (1990) barometer yielded negative pressures for some of these garnet peridotites; thus computation of the present garnet-olivine geothermometer is based on the input pressures determined by Harley's (1984b) barometer because this barometer seldom yields negative pressures. It is noted that the ferric iron contents in all the ferromagnesian minerals (garnet, olivine, clinopyroxene and olivine) of the garnet peridotites are very low, and negative values of Fe^{3+} contents are always obtained for these minerals according to the method of Droop (1987). This is in accordance with the suggestion of Krogh & Carswell (1995) and Ravna & Paquin (2003) that ferric iron contents of ultramafic minerals are generally considered to be negligible. Thus in the thermobarometric computation ferric iron contents of the minerals are neglected.

From Table S4 and Fig. 2 it is found that the present garnet-olivine thermometer yielded similar temperatures as that of the garnet-clinopyroxene thermometer (Ellis & Green, 1979; Ravna, 2000) and the clinopyroxene-orthopyroxene thermometer (Brey & Köhler, 1990) for the garnet peridotites from mantle xenoliths, orogenic garnet peridotites and metagabbros. This suggests that the present garnet-olivine thermometer is applicable to garnet peridotites and metagabbros.

The Adirondack olivine-bearing metagabbros provide another opportunity to test the applicability of the present thermodynamically consistent garnet-olivine geothermometer and garnet-olivine-plagioclase geobarometer. In the eastern Adirondack Mountains, New York, USA, quartz-absent, olivine-bearing metagabbros occur mainly as dykes, sills or small stocks from tens of metres to several kilometres in diameter (Johnson & Essene, 1982). Texturally, two kinds of metagabbros were found in this area. One kind of metagabbro is finer grained with equant metamorphic textures and without reaction rims. Reaction coronas were found in another kind of metagabbros. Although coronas were found in these samples which usually record different reaction histories and different mineral assemblages, the coronal minerals seem to have equilibrated chemically at or near peak metamorphic conditions in the Adirondacks (Valley & Bohlen, 1979). Inhomogeneity in coronal phases is very slight, and there is no significant chemical zoning in any of the phases, contrary to what one might expect in rocks which texturally show partially completed reactions (Johnson & Essene, 1982). In fact, phases which occur in the same rock both in rimming relationships and as equant, apparent equilibrium phases, are essentially identical in composition. All these suggest that a nearly complete thermodynamic equilibrium has been reached (Johnson & Essene, 1982). Simultaneously applying the present garnet-olivine-plagioclase thermobarometers yielded the peak metamorphic *P–T* conditions to be around 690–780 °C and 3.8–5.9 kbar within the sillimanite stability field (Table 1, Fig. 2d), and the two kinds of metagabbros show no *P–T* variations (Fig. 2d) which again suggests that equilibrium has been reached during the metamorphic event. The temperatures yielded by the

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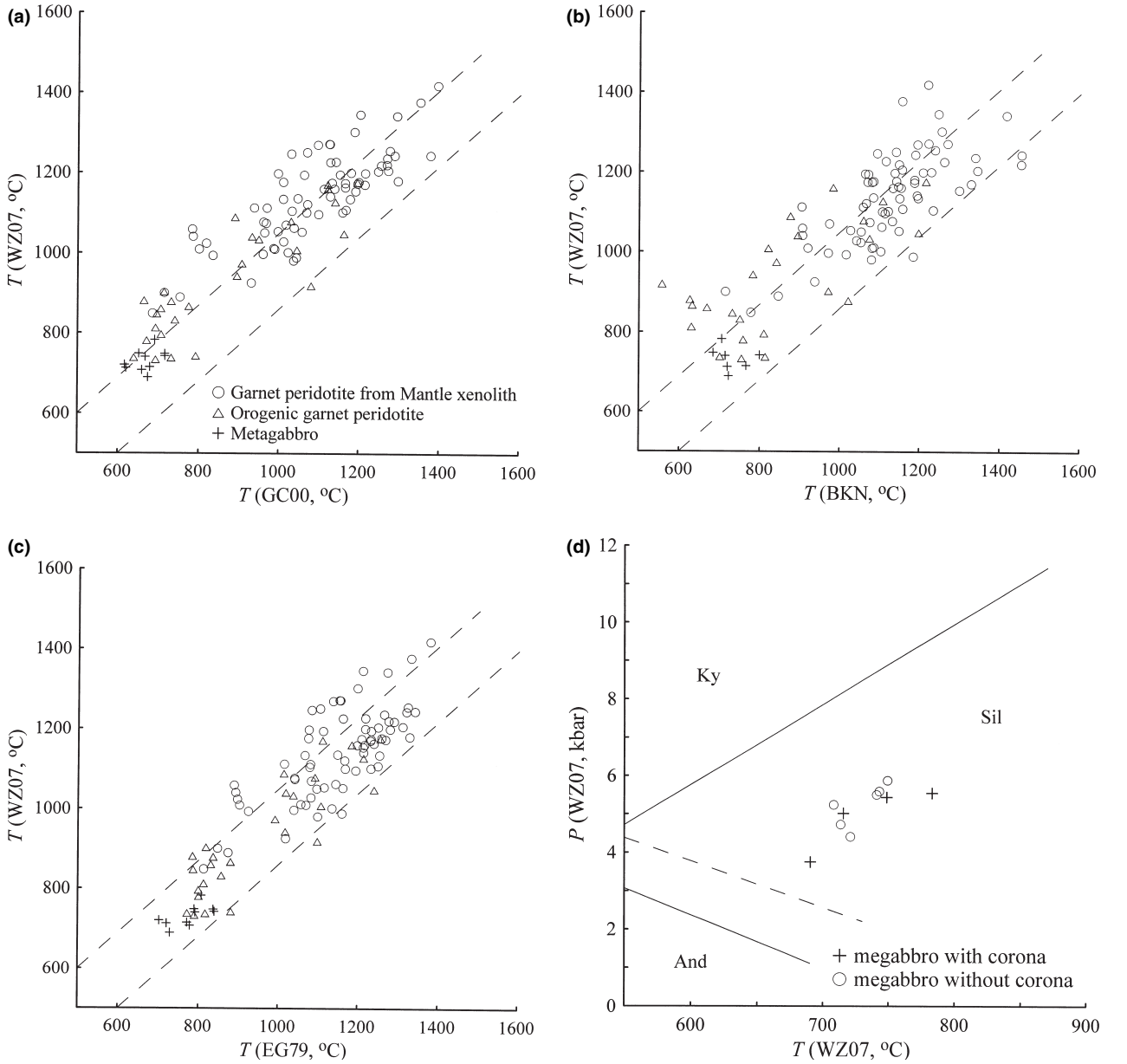


Fig. 2. Applications of the present garnet-olivine-plagioclase thermobarometers and other thermometers to garnet peridotites from mantle xenoliths, orogenic garnet peridotites and metagabbros (Table S4). Dashed lines represent ±100 °C temperature deviations. (a) Relationships between the present garnet-olivine temperatures, *T*(WZ07) and the garnet-clinopyroxene temperatures, *T*(GC00) (Ravna, 2000); (b) relationships between the present garnet-olivine temperatures, *T*(WZ07) and the two-pyroxene temperatures, *T*(BKN) (Brey & Köhler, 1990); (c) relationships between the present garnet-olivine temperatures, *T*(WZ07) and the garnet-clinopyroxene temperatures, *T*(EG79) (Ellis & Green, 1979); and (d) *P*–*T* determinations of the metagabbros from the Adirondack Mountains, USA (Johnson & Essene, 1982) by simultaneously applying the present garnet-olivine thermometer and garnet-olivine-plagioclase barometer derived in this paper. Solid lines represent the aluminosilicate equilibria of Holdaway & Mukhopadhyay (1993), whereas the dashed line represents the andalusite = sillimanite equilibrium of Pattison (1992).

present garnet-olivine thermometer are similar to those by the garnet-clinopyroxene (Fig. 2a, c) and clinopyroxene-orthopyroxene thermometers (Fig. 2b).

Actually, barometry in the Adirondacks seems to give results independent of rock types and pressures vary smoothly across the terrane from about 6 kbar in the Lowlands and southern Adirondacks to roughly 8 kbar in the Highlands, as suggested by Johnson & Essene (1982). In fact, metamorphic pressures in the Adirondacks have been constrained by several independent equilibria. Brown *et al.* (1978) estimated a metamorphic pressure of 6.5 ± 0.5 kbar at 625 ± 25 °C by sphalerite barometry and calcite-dolomite thermometry in NW Adirondacks. The coexistence of

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Table 1. Pressures and temperatures determined for the Adirondacks metagabbros

Sample	*T*(WZ07) (°C)	*P*(WZ07) (bar)	*T*(79) (°C)	*T*(90) (°C)	*T*(84) (°C)	*P*(84) (bar)	*T*(80) (°C)	*T*(BKN) (°C)	*P*(BKN) (bar)	*T*(GC00) (°C)
I87-1	716	5016	671	870	728	10, 806	725	765	10, 598	679
SC-2	749	5435	699	794	756	8827	650	684	1492	716
N-3	783	5547	761	888	769	11, 241	750	705	4529	691
I87-4	690	3751	643	1038	653	14, 835	725	722	32, 913	674
AS-1	743	5591	695	775	770	9742	750	799	5919	716
TL-1	741	5503	724	809	799	12, 368	725	714	4878	668
W-2	749	5874	688	745	773	10, 423	700	*	*	652
LP-2	708	5239	642	739	732	10, 034	750	*	*	659
LL-1	713	4727	666	830	728	14, 387	700	719	11, 692	620
233-1	721	4409	691	927	705	10, 638	700	*	*	617

T(WZ07) and *T*(WZ07) are temperatures and pressures determined by simultaneously applying the garnet-olivine thermometer and garnet–olivine–plagioclase barometer derived in this paper, respectively. *T*(79) and *T*(90) are temperatures determined by the garnet-olivine thermometer of O'Neill & Wood (1979) and Brey & Köhler (1990), respectively. *T*(84) and *P*(84) are temperatures and pressures simultaneously determined by the garnet-orthopyroxene thermometer and Al-in-orthopyroxene barometer of Harley (1984a,b), respectively. *T*(80) are temperatures determined using oxide thermometry (Bohlen *et al*., 1980). *T*(BKN) and *P*(BKN) are simultaneously determined clinopyroxene–orthopyroxene temperatures and Al-in-orthopyroxene pressures (Brey & Köhler, 1990), respectively. *T*(GC00) are garnet-clinopyroxene temperatures (Ravna, 2000).

akermanite, monticellite and wollastonite at Cascade Slide restricts pressure to 7.4 ± 1.0 kbar at 750 ± 30 °C (Valley & Essene, 1980). A single kyanite occurrence at the Blue Mountain in close proximity to several sillimanite localities, requires a pressure of 7.6 ± 0.5 kbar at 730 ± 30 °C (Bohlen *et al*., 1980). All these are slightly higher than our estimates derived by the present garnet-olivine-plagioclase thermobarometers (Table 1). However, the present *P–T* determinations all plot in the sillimanite-stability field (Fig. 2d), which is consistent with the ubiquitous appearance of sillimanite in the Adirondacks (Johnson & Essene, 1982), and the *P–T* estimates are similar to that derived from other thermobarometers by Spear & Markussen (1997). On the contrary, the Al-in-orthopyroxene barometer (Brey & Köhler, 1990) yielded negative pressure estimates for some samples (Table 1) possibly because Cr_2O_3 contents of the minerals from the rocks in the Adirondacks are quite negligible. The Harley (1984a,b) thermobarometers, however, yielded significantly higher pressures which put all the samples into the kyanite stability field (Table 1) which is not the case.

DISCUSSION

The garnet-olivine thermometer derived in this paper incorporates mineralogical data of both iron-rich and magnesium-rich systems, and thus reproduces the experimental temperatures much better than those by previous versions (Fig. 1). The O'Neill & Wood (1979) garnet-olivine thermometer is less successful in reproducing the experimental temperatures, although it is derived by Fe- and Mg-rich minerals and includes the non-ideal mixing properties of both garnet and olivine and even the volume changes of the phases with changing *P* and *T*. The relative poorer performance of the Brey & Köhler (1990) garnet-olivine thermometer in matching the experimental temperatures may lie in that it does not include the Fe-rich data and the non-ideal mixing properties of either garnet or olivine. Thus, it is suggested that the present thermometer be applied as a practical tool in determining metamorphic temperatures in medium-high-temperature to ultrahigh-temperature metamorphic rocks of mafic and ultramafic origin, although its precision is not so perfect.

The present garnet-olivine-plagioclase barometer is derived on the basis of the tight reversals of Bohlen *et al*. (1983) and Perkins & Vielzeuf (1992) and it incorporates the non-ideal mixing properties of garnet, olivine and plagioclase as well as the heat capacities, thermal expansion coefficients and compressibility coefficients of the phases. It has returned identical pressures as those of the experimental reversals and reasonable pressures for the Adirondack metagabbros. Although a literature search did not collate much more natural data to test the applicability of this barometer, we believe that it is a practical barometer applicable to metamorphic rocks, and both *P* and *T* can be simultaneously determined in combination with the present garnet-olivine thermometer, even the assemblage garnet + olivine + plagioclase is probably restricted to mafic rocks and is expected to be very rare.

Iteration is needed in applying the garnet-olivine-plagioclase barometer, and it is often easy to reach pressure convergence. An MS Excel spreadsheet (Table S5) is deposited as an electronic supplementary material on the journal's website, acting as the thermobarometry program for readers' use. The interested reader may also contact the authors for gaining the spreadsheet.

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SUPPLEMENTARY MATERIAL

The authors have provided supplementary appendices to the paper, which are available from http://www.blackwell-synergy.com.

Table S1. Experimental data used in calibrating the garnet–olivine geothermometer.

Table S2. Activity model expressions of garnet and plagioclase.

Table S3. Experimental data used in calibrating the garnet–olivine–plagioclase geobarometer.

Table S4. Applications of different geothermometers and geobarometers to natural garnet peridotites and metagabbros.

Table S5. Iterative Excel spreadsheet in applying the present garnet–olivine geothermometer and garnet-olivine-plagioclase geobarometer.

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