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Non-ideal Mg-Fe binary mixing in cordierite: Constraints from experimental data on Mg-Fe partitioning in garnet and cordierite and a reformulation of garnet-cordierite geothermometer

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Abstract. The non-ideal regular Mg-Fe binary in cordierite has been derived through multivariate linear regression of the expression $RT \ln K_D + (P-1)\Delta V^0_{1,298}$ along with updated subregular mixing parameter of almandine-pyrope solution (Hackler and Wood 1989; Berman 1990). The data base used for multivariate analyses consists of published experimental data ($n = 177$) on Mg-Fe partitioning between garnet and cordierite in the P-T range 650–1050°C and 4–12 K bar. The non-ideality can be approximated by temperature-dependent Margules parameters. The retrieved values of $\Delta H^0_{\langle T\rangle}$ and $\Delta S^0_{\langle T\rangle}$ of exchange reaction between garnet and cordierite and enthalpy and entropy of mixing of Mg-Fe cordierite were combined with recent quaternary (Fe-Mg-Ca-Mn) mixing data in garnet to obtain the geothermometric expressions to determine temperature (T Kelvin):

$T(HW) = 6832 + 0{\cdot}031(P-1) - \{166(X^{\text{Gt}}_{\text{Mg}})^2 - 506(X^{\text{Gt}}_{\text{Fe}})^2 + 680X^{\text{Gt}}_{\text{Fe}}X^{\text{Gt}}_{\text{Mg}} + 336(X_{\text{Ca}} + X_{\text{Mn}})$ $(X_{\text{Mg}} - X_{\text{Fe}})^{\text{Gt}} - 3300X^{\text{Gt}}_{\text{Ca}} - 358X^{\text{Gt}}_{\text{Mn}}\} + 954(X_{\text{Fe}} - X_{\text{Mg}})^{\text{Crd}}/1{\cdot}987 \ln K_D + 3{\cdot}41 + 1{\cdot}5X^{\text{Gt}}_{\text{Ca}}$ $+ 1{\cdot}23(X_{\text{Fe}} - X_{\text{Mg}})^{\text{Crd}}$

$T(\text{Br}) = 6920 + 0{\cdot}031(P-1) - \{18(X^{\text{Gt}}_{\text{Mg}})^2 - 296(X^{\text{Gt}}_{\text{Fe}})^2 + 556X^{\text{Gt}}_{\text{Fe}}X^{\text{Gt}}_{\text{Mg}} - 6339X^{\text{Gt}}_{\text{Ca}}X^{\text{Gt}}_{\text{Mg}}$ $- 99(X^{\text{Gt}}_{Ca})^2 + 4687X^{\text{Gt}}_{\text{Ca}}(X_{\text{Mg}} - X^{\text{Gt}}_{\text{Fe}}) - 4269X^{\text{Gt}}_{\text{Ca}}X^{\text{Gt}}_{\text{Fe}} - 358X^{\text{Gt}}_{\text{Mn}}\} + 640(X_{\text{Fe}} - X_{\text{Mg}})^{\text{Crd}}$ $/1{\cdot}987 \ln K_D + 3{\cdot}40 + 1{\cdot}095(X^{\text{Gt}}_{\text{Ca}})^2 + 1{\cdot}1X^{\text{Gt}}_{\text{Ca}}X^{\text{Gt}}_{\text{Mg}} + 1{\cdot}09X^{\text{Gt}}_{\text{Ca}}X^{\text{Gt}}_{\text{Fe}} + 0{\cdot}78(X_{\text{Fe}} - X_{\text{Mg}})^{\text{Crd}}$ $+ 1{\cdot}90X^{\text{Gt}}_{\text{Ca}}(X_{\text{Mg}} - X_{\text{Ca}})^{\text{Gt}}.$

Keywords. Geothermometer; equilibrium; regression; mixing parameters.

1. Introduction

Mg-Fe exchange between coexisting garnet and cordierite is known to be significantly dependent on temperature of equilibration. Due to the common occurrence of this mineral pair in medium to high-grade metamorphic rocks, the garnet-cordierite geothermometer has wide application. The calibrations based on $K^{\text{Gt}-\text{Crd}}_{\text{DFe}-\text{Mg}}$ from metamorphic rocks of varying metamorphic grades have been proposed by Thompson (1976), Bhattacharya *et al* (1988) and others. Besides this the Mg-Fe exchange equilibrium between garnet and cordierite has been experimentally studied and calibrated for geothermometry (Hensen and Green 1971; Hensen 1977; Perchuk and Lavrent'eva 1983; Perchuk *et al* 1985; Aranovich and Podlesskii 1989; and Nichols *et al* 1992). Bhattacharya (1993) calibrated this equilibrium using the internally consistent data set of Berman (1988) and Holland and Powell (1990). The estimates of temperature through these geothermometers differ because of ideal or non-ideal mixing of Fe-Mg-Ca-Mn in garnet and different $\ln K_D$ versus $1/T$ slope. For the Mg-Fe mixing properties of cordierite, many authors except, Bhattacharya *et al* (1988), have assumed ideal Mg-Fe mixing in cordierite.

The main objectives of this paper are: **(a)** to derive new thermodynamic data on Mg-Fe exchange equilibria between garnet and cordierite from experimental data ($n = 177$) in the FeO-MgO-Al_2O_3-SiO_2 system; **(b)** to determine the Margules parameters related to non-ideal Mg-Fe mixing in cordierite on the basis of recent data on Mg, Fe partitioning in almandine-pyrope system, and **(c)** to finally propose a garnet-cordierite geothermometer for application to metamorphic rocks of different grade.

2. Thermodynamic background

The Mg and Fe exchange between garnet and cordierite (abbreviated Gt and Crd respectively) can be expressed as:

$$\underset{\text{Fe-cordierite}}{1/2\,\mathrm{Fe_2Al_4Si_5O_{18}}} + \underset{\text{Pyrope}}{1/3\,\mathrm{Mg_3Al_2Si_3O_{12}}} = \underset{\text{Mg-cordierite}}{1/2\,\mathrm{Mg_2Al_4Si_5O_{18}}} + \underset{\text{Almandine}}{1/3\,\mathrm{Fe_3Al_2Si_3O_{12}}}. \tag{1}$$

At equilibrium the equation is:

$$\Delta G_{PT}(1) = \Delta H^0_{1,298} + \int_{298}^{T} \Delta C^0 p(T)\mathrm{d}T - T[\Delta S^0_{1,298} + \int_{298}^{T} \Delta C^0 p(T)\mathrm{d}T/T] + \int_{1}^{P} \Delta V^0(P)\mathrm{d}P + RT\ln K_D + RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}} + RT\ln(\gamma_{\mathrm{Mg}}/\gamma_{\mathrm{Fe}})^{\mathrm{Crd}}, \tag{2}$$

where, $\Delta G_{PT}(1)$ is the molar Gibbs free energy change related to reaction (1) at specified $P-T$. $\Delta H^0_{1,298}$, $\Delta S^0_{1,298}$ and $\Delta V^0_{1,298}$ are the standard state changes in enthalpy, entropy and volume respectively between pure phases at 1 bar and 298 (K) of the reaction (1); T is temperature (K); P is pressure (bar); $\Delta C^0 p$ is change in heat capacity of the reaction (1); γ_i^J is the activity coefficient of the component i in phases J and R is the universal gas constant ($1{\cdot}987\,\mathrm{cal\,K^{-1}}$).

A linear relation of $\ln K + (P-1)\Delta V^0_{1,298}/RT$ versus $1/T$(K) (figure 1) suggests that ΔC^0_p is negligible or cannot be resolved in the temperature range of the present study, ΔH^0 and ΔS^0 in equation (2) are therefore the average standard enthalpy and entropy differences respectively of the reaction for the experimental range of temperature (i.e. $\Delta H^0_{\langle T\rangle}$ and $\Delta S^0_{\langle T\rangle}$ proposed by Chatterjee 1991, p. 124). As the ΔV^0 of the reaction is small, the integral term of ΔV^0 can be ignored, and thus equation (2) can be written as:

$$\Delta G_{PT}(1) = 0 = \Delta H^0 - T\Delta S^0 + (P-1)\Delta V^0_{1,298} + RT\ln K, \tag{3}$$

where K is the equilibrium constant of reaction (1), $K = RT\ln K_D + RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}} + RT\ln(\gamma_{\mathrm{Mg}}/\gamma_{\mathrm{Fe}})^{\mathrm{Crd}}$, $K_D = (X_{\mathrm{Fe}}/X_{\mathrm{Mg}})^{\mathrm{Gt}} \cdot (X_{\mathrm{Mg}}/X_{\mathrm{Fe}})^{\mathrm{Crd}}$; $X_{\mathrm{Mg}}^{\mathrm{Gt/Crd}} = \mathrm{Mg}/(\mathrm{Mg}+\mathrm{Fe})$; $X_{\mathrm{Fe}}^{\mathrm{Gt/Crd}} = \mathrm{Fe}/(\mathrm{Mg}+\mathrm{Fe})$.

3. Activity coefficient in garnet and cordierite

The activity coefficients in garnet $\gamma_{\mathrm{Fe}}^{\mathrm{Gt}}$ and $\gamma_{\mathrm{Mg}}^{\mathrm{Gt}}$, were derived by using the subregular solution of Mg-Fe mixing expressions in garnet of Ganguly and Saxena (1984) (equation 4) and Berman (1990) (equation 5).

$$RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}} = W_{\mathrm{Fe-Mg}}X_{\mathrm{Mg}}^2 - W_{\mathrm{Mg-Fe}}X_{\mathrm{Fe}}^2 + 2(W_{\mathrm{Mg-Fe}} - W_{\mathrm{Fe-Mg}})X_{\mathrm{Fe}}X_{\mathrm{Mg}}. \tag{4}$$

$$RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}} = W_{223}X_{\mathrm{Mg}}^2 - W_{233}X_{\mathrm{Fe}}^2 + 2(W_{233} - W_{223})X_{\mathrm{Fe}}X_{\mathrm{Mg}}. \tag{5}$$

The Fe-Mg mixing parameter (W) is generally expressed by the following equation:

$$W = W_H - TW_S + PW_V, \tag{6}$$

where, W_H, W_S and W_V are the non-ideal mixing parameters for enthalpy, entropy and volume respectively (Thompson 1976; Ganguly and Saxena 1984). By ignoring W_V and subtracting $\gamma_{\mathrm{Fe}}^{\mathrm{Crd}}$ from $\gamma_{\mathrm{Mg}}^{\mathrm{Crd}}$, equation (7) is obtained using the regular solution of Fe-Mg mixing.

$$RT\ln(\gamma_{\mathrm{Mg}}/\gamma_{\mathrm{Fe}}) = W_{H,\mathrm{Fe-Mg}}(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} - TW_{S,\mathrm{Fe-Mg}}(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}}. \tag{7}$$

Substituting equation (7) and (4) in equation (3) with $W_{\mathrm{Fe-Mg}}^{\mathrm{Gt}} = 166$ cal and $W_{\mathrm{Mg-Fe}}^{\mathrm{Gt}} = 506$ cal per cation (Hackler and Wood 1989) and rearranging gives:

$$\begin{aligned} RT\ln K_D - 0{\cdot}031(P-1) + 166X_{\mathrm{Mg}}^2 - 506X_{\mathrm{Fe}}^2 + 2(506-166)X_{\mathrm{Fe}}X_{\mathrm{Mg}} \\ = [Z] = -\Delta H + T\Delta S - W_{H,\mathrm{Fe-Mg}}(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} \\ + TW_{S,\mathrm{Fe-Mg}}(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}}. \end{aligned} \tag{8}$$

After substitution of equations (7) and (5) in equation (3) and using subregular Fe-Mg interaction parameter of Berman (1990), $W_{223} = 18$ and $W_{233} = 296$, equation (9) can be obtained after rearrangement:

$$\begin{aligned} RT\ln K_D - 0{\cdot}031(P-1) + 18X_{\mathrm{Mg}}^2 - 196X_{\mathrm{Fe}}^2 + 2(196-18)X_{\mathrm{Fe}}X_{\mathrm{Mg}} \\ = [Z1] = -\Delta H + T\Delta S - W_{H,\mathrm{Fe-Mg}}(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} \\ + TW_{S,\mathrm{Fe-Mg}}(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}}. \end{aligned} \tag{9}$$

If the terms on the left hand side of equations (8) and (9) are known, then four unknown parameters on the right hand side can be estimated by multivariate regression. The $V_{1,298}^0$ of reaction (1) is ($-0{\cdot}031$ cal bar^{-1}) calculated from the data of Holland and Powell (1990). K_D has been calculated from the experimental data related to Fe-Mg exchange reaction between garnet and cordierite (Hensen and Green 1971; Hensen 1977; Perchuk and Lavrent'eva 1983; Aranovich and Podlesskii 1983 and Bertrand *et al* 1991) for $P-T$ range 650–1050°C and 4–12 Kbar. $[Z]$ and $[Z1]$ of the left hand side of equations (8) and (9) are computed at experimental P and T of equilibration (table 1). $[Z]$ and $[Z1]$ were chosen as the dependent variables and three terms (ΔS, $W_{H,\mathrm{Fe-Mg}}^{\mathrm{Crd}}$ and $W_{S,\mathrm{Fe-Mg}}^{\mathrm{Crd}}$) of the right hand side of equations (8) and (9) as the independent variables and ΔH as the regression constant. The retrieved values of temperature dependent Margules parameters in cordierite, with 97% confidence level, derived from equations (8) and (9) respectively, are:

$$W_{G,\mathrm{Fe-Mg}}^{\mathrm{Crd}} = 954(\pm 329) - 1{\cdot}23T(\pm 0{\cdot}48). \tag{8a}$$

$$W_{G,\mathrm{Fe-Mg}}^{\mathrm{Crd}} = 640(\pm 312) - 0{\cdot}78T(\pm 0{\cdot}26). \tag{9a}$$

Table 1. [Z] and [$Z1$] values. Equations (8) and (9) computed from the two sub-regular mixing models for Fe-Mg garnets on the basis of experimental P, T, X^{Gt}_{Fe} and X^{Crd}_{Fe} data.

S. No	P(bar)	T(K)	$(X_{Fe}-X_{Mg})^{Crd}$	$T(X_{Fe}-X_{Mg})^{Crd}$	Z	$Z1$
(a) Hensen and Green (1971)						
1.	9000	1173	−0·62	−727·6	3176·1	3038·0
2.	7200	1223	−0·04	−48·9	2603·0	2523·7
3.	8100	1273	−0·60	−763·8	3432·2	3207·3
4.	9300	1273	−0·78	−992·9	4033·6	3759·8
(b) Hensen (1977)						
5.	9000	1273	−0·64	−814·7	2645·7	2557·4
(c) Perchuk and Lavrenteva (1983)						
6.	6000	923	−0·852	−786·3	4010·0	3969·4
7.	6000	923	−0·640	−590·7	3801·8	3852·5
8.	6000	923	−0·874	−806·7	4019·6	3965·1
9.	6000	923	−0·620	−512·3	3914·4	3894·1
10.	6000	923	−0·300	−276·9	3582·2	3705·1
11.	6000	923	−0·320	−295·4	3607·2	3697·7
12.	6000	973	−0·540	−525·4	3752·6	3820·5
13.	6000	973	−0·510	−496·2	3594·1	3661·9
14.	6000	973	−0·540	−525·4	3590·5	3649·8
15.	6000	973	−0·360	−350·2	3410·3	3505·1
16.	6000	973	−0·420	−408·6	3588·7	3678·9
17.	6000	973	−0·480	−467·0	3610·3	3687·0
18.	6000	973	−0·460	−447·6	3598·8	3679·9
19.	6000	973	−0·520	−505·9	3482·2	3541·5
20.	6000	973	−0·140	−136·2	3410·3	3542·9
21.	6000	973	−0·640	−622·7	3583·7	3609·8
22.	6000	973	−0·780	−758·9	3844·8	3825·7
23.	6000	973	−0·580	−564·3	3507·5	3549·9
24.	6000	973	−0·134	−130·4	3843·4	3990·9
25.	6000	973	−0·070	−681·1	3577·7	3586·6
26.	6000	973	−0·040	−038·9	3688·2	3835·6
27.	6000	973	−0·600	−538·8	3777·6	3828·3
28.	6000	973	−0·680	−661·6	3713·3	3731·6
29.	6000	973	−0·060	−058·3	3412·3	3544·9
30.	6000	973	−0·586	−570·2	3687·7	3738·1
31.	6000	973	−0·480	−467·1	3652·9	3731·8
32.	6000	973	−0·560	−544·8	3702·7	3761·9
33.	6000	973	−0·700	−681·1	3649·2	3656·1
34.	6000	973	−0·880	−856·2	3831·1	3757·4
35.	6000	973	−0·544	−529·3	3692·0	3755·5
36.	6000	973	−0·780	−758·9	3809·3	3788·5
37.	6000	973	−0·600	−583·8	3663·1	3707·5
38.	6000	973	−0·338	−328·8	3525·3	3629·8
39.	6000	973	−0·544	−529·3	3607·0	3661·1
40.	6000	973	−0·464	−451·5	3529·1	3605·8
41.	6000	973	−0·464	−451·5	3679·5	3763·8
42.	6000	973	−0·814	−792·0	3809·9	3771·8
43.	6000	973	−0·342	−332·7	3445·0	3544·9
44.	6000	973	−0·442	−430·1	3509·9	3591·0
45.	6000	973	−0·820	−797·8	3917·3	3881·1

(*Continued*)

Table 1. (*Continued*)

S. No	P(bar)	T(K)	$(X_{\mathrm{Fe}}-X_{\mathrm{Mg}})^{\mathrm{Crd}}$	$T(X_{\mathrm{Fe}}-X_{\mathrm{Mg}})^{\mathrm{Crd}}$	Z	$Z1$
46.	6000	973	−0·600	−583·8	3777·6	3828·3
47.	6000	973	−0·380	−369·7	3599·0	3698·4
48.	6000	973	−0·550	−535·1	3646·6	3705·8
49.	6000	973	−0·890	−865·9	3772·8	3691·5
50.	6000	973	−0·480	−467·8	3120·2	3171·0
51.	6000	973	0·040	038·9	3343·6	3496·1
52.	6000	973	−0·160	−155·7	3423·0	3553·2
53.	6000	1023	−0·380	−380·7	3405·2	3450·3
54.	6000	1023	−0·640	−654·7	3625·6	3643·8
55.	6000	1023	−0·320	−327·3	3251·7	3338·7
56.	6000	1023	−0·360	−368·3	3405·7	3491·3
57.	6000	1023	−0·416	−425·5	3485·8	3562·5
58.	6000	1023	−0·476	−486·9	3498·0	3560·3
59.	6000	1023	−0·320	−327·3	3320·6	3410·8
60.	6000	1023	−0·480	−491·0	3410·1	3466·8
61.	6000	1023	−0·648	−662·9	3554·5	3566·1
62.	6000	1023	−0·818	−836·8	3587·2	3530·2
63.	6000	1023	−0·372	−380·5	3442·6	3527·4
64.	6000	1023	−0·400	−409·2	3408·6	3485·3
65.	6000	1023	−0·464	−474·7	3393·5	3453·7
66.	6000	1023	−0·560	−572·8	3660·3	3706·8
67.	6000	1023	−0·340	−347·8	3356·7	3440·1
68.	6000	1023	−0·172	−175·9	3303·6	3420·3
69.	6000	1023	−0·232	−237·3	3301·6	3407·9
70.	6000	1023	−0·300	−306·9	3227·1	3317·3
71.	6000	1023	−0·480	−497·0	3375·7	3430·7
72.	6000	1023	−0·580	−593·3	3464·8	3495·0
73.	6000	1023	−0·620	−634·3	3566·1	3588·3
74.	6000	1023	−0·760	−777·5	3622·0	3592·5
75.	6000	1023	−0·749	−766·2	3692·0	3624·3
76.	6000	1023	−0·338	−345·8	3228·0	3420·8
77.	6000	1073	−0·220	−236·0	3233·8	3332·3
78.	6000	1073	−0·460	−493·6	3353·0	3293·7
79.	6000	1073	−0·320	−343·4	3296·5	3377·7
80.	6000	1073	−0·240	−257·5	3302·4	3399·9
81.	6000	1073	−0·080	−085·8	3126·7	3244·8
82.	6000	1073	−0·164	−175·9	3203·5	3310·8
83.	6000	1073	−0·660	−708·2	3486·9	3482·4
84.	6000	1073	−0·830	−890·6	3524·2	3453·6
85.	6000	1073	−0·520	−557·9	3397·7	3427·9
86.	6000	1073	−0·220	−236·0	3254·8	3354·2
87.	6000	1073	−0·100	−107·3	3161·8	3278·1
88.	6000	1123	−0·400	−449·2	3180·9	3230·8
89.	6000	1123	−0·160	−179·7	3033·9	3128·1
90.	6000	1123	−0·140	−157·2	3032·4	3130·8
91.	6000	1123	−0·096	−107·8	3100·6	3209·3
92.	6000	1123	−0·222	−249·3	3035·4	3118·4
93.	6000	1123	−0·240	−269·5	3080·3	3161·4
94.	6000	1123	−0·340	−381·8	3167·5	3231·1
95.	6000	1123	−0·310	−348·1	3056·0	3123·9
96.	6000	1123	−0·264	−296·5	3285·2	3369·1

(*Continued*)

Table 1. (*Continued*)

S. No	P(bar)	T(K)	$(X_{\mathrm{Fe}}-X_{\mathrm{Mg}})^{\mathrm{Crd}}$	$T(X_{\mathrm{Fe}}-X_{\mathrm{Mg}})^{\mathrm{Crd}}$	Z	$Z1$
97.	6000	1123	−0·810	−909·6	3485·0	3416·5
98.	6000	1123	−0·660	−741·2	3285·6	3264·8
99.	6000	1123	−0·596	−669·3	3242·8	3238·8
100.	6000	1123	−0·544	−610·9	3263·7	3278·5
101.	6000	1123	−0·462	−518·8	3351·6	3393·6
102.	6000	1123	−0·334	−375·1	3242·5	3310·9
103.	6000	1123	−0·120	−134·8	3001·6	3102·4
104.	6000	1123	−0·440	−494·1	3397·4	3447·3
105.	6000	1123	−0·300	−336·9	3213·5	3287·9
106.	6000	1123	−0·460	−516·6	3201·8	3237·2
107.	6000	1123	−0·392	−440·2	3202·8	3255·7
108.	6000	1123	0·006	006·7	2950·0	3069·6
109.	6000	1123	−0·622	−698·5	3409·4	3406·7
110.	6000	1123	0·116	130·2	2960·8	3096·4
111.	6000	1123	−0·044	−049·4	2998·4	3111·8
112.	6000	1123	−0·168	−188·7	3037·0	3130·4
113.	6000	1123	−0·300	−336·9	3263·6	3340·3
114.	6000	1123	−0·386	−433·5	3314·5	3375·5
115.	6000	1123	−0·460	−516·6	3175·6	3209·8
116.	6000	1173	−0·224	−262·7	3174·4	3306·7
117.	6000	1173	−0·038	−044·6	2998·9	3106·6
118.	6000	1173	−0·122	−143·1	2898·0	2988·6
119.	6000	1173	−0·356	−417·6	3067·2	3115·8
120.	6000	1173	−0·656	−769·5	3463·6	3441·0
121.	6000	1173	−0·360	−422·3	3079·8	3128·1
122.	6000	1173	−0·344	−403·5	3183·4	3239·5
123.	6000	1173	−0·168	−197·1	2973·6	3037·6
124.	6000	1173	−0·500	−586·5	3085·4	3138·2
125.	6000	1173	−0·380	−445·2	3149·1	3195·7
126.	6000	1173	−0·160	−187·7	2962·4	3048·1
127.	6000	1173	−0·086	−100·9	2943·6	3042·5
128.	6000	1223	−0·062	−075·8	2630·2	2718·1
129.	6000	1223	0·140	171·2	2369·5	2482·9
130.	6000	1223	−0·240	−293·5	2704·1	2759·1
131.	6000	1223	0·200	244·6	2619·1	2749·2
132.	6000	1223	0·022	026·9	2589·9	2691·4
133.	6000	1223	−0·074	−090·5	2508·0	2588·7
134.	6000	1223	−0·154	−188·3	2540·3	2606·5
135.	6000	1223	−0·440	−538·1	2856·2	2871·0
136.	6000	1223	0·226	276·4	2756·2	2893·7
137.	6000	1223	0·254	310·6	2610·4	2747·9
138.	6000	1223	0·110	134·5	2665·0	2783·1
139.	6000	1223	0·002	002·4	2683·5	2784·2
140.	6000	1223	−0·120	−146·8	2908·4	2995·8
141.	6000	1223	−0·324	−396·3	2782·5	2822·0
142.	6000	1223	−0·306	−374·2	2725·1	2766·2
143.	6000	1223	−0·194	−237·2	2677·0	2740·9
144.	6000	1223	−0·088	−107·6	2587·1	2668·2
145.	6000	1223	−0·014	−017·1	2591·3	2689·3
146.	6000	1223	−0·860	−1051·8	2998·9	2895·0
147.	6000	1223	−0·634	−775·3	3033·8	3001·6

(*Continued*)

Table 1. (*Continued*)

S. No	P(bar)	T(K)	$(X_{Fe}-X_{Mg})^{Crd}$	$T(X_{Fe}-X_{Mg})^{Crd}$	Z	$Z1$
148.	6000	1223	−0·718	−878·1	3003·6	2944·7
149.	6000	1223	−0·800	−978·4	3026·2	2942·0
150.	6000	1223	−0·850	−1039·6	2903·6	2801·2
151.	6000	1223	−0·040	−048·9	2470·8	2556·5
152.	6000	1223	0·122	149·2	2653·7	2773·3
153.	6000	1273	−0·360	−458·3	2887·8	2919·5
154.	6000	1273	−0·132	−168·0	2724·8	2796·6
155.	6000	1273	−0·277	−346·3	2827·7	2874·3
(d) Aranovich and Podleskkii (1983)						
156.	4000	973	−0·12	−116·7	3293·2	3450·7
157.	5000	973	0·10	097·3	3289·1	3421·7
158.	6000	973	0·38	369·7	3405·0	3498·2
159.	8000	973	0·78	758·9	3774·1	3755·0
160.	5000	1023	−0·12	−116·7	3064·8	3212·3
161.	8000	1023	0·66	642·2	3471·9	3478·6
(e) Bertrand *et al* (1991)						
162.	10000	1173	−0·82	−961·8	3176·1	3093·7
163.	10000	1173	−0·72	−844·6	1781·1	1701·2
164.	10000	1173	−0·72	−844·5	2015·4	1932·9
165.	10000	1173	−0·68	−797·6	2933·8	2890·8
166.	10000	1273	−0·58	−738·3	2365·2	2325·6
167.	10000	1273	−0·58	−738·3	2744·5	2715·0
168.	10000	1273	−0·60	−763·8	2806·0	2773·1
169.	10000	1273	−0·64	−814·7	2741·1	2694·9
170.	10000	1273	−0·67	−841·6	3112·9	3073·3
171.	11000	1273	−0·74	−942·0	2733·2	2659·3
172.	11000	1273	−0·68	−865·6	3069·3	3023·1
173.	11000	1273	−0·72	−916·5	2847·1	2782·1
174.	12000	1273	−0·78	−992·9	3100·4	3023·6
175.	10000	1298	−0·60	−778·8	3059·4	3033·4
176.	10000	1298	−0·72	−943·5	3639·3	3596·4
177.	10000	1323	−0·62	−820·3	2706·8	2727·9

4. Formulation of garnet-cordierite geothermometer

4.1 *ΔH and ΔS of reaction (1):*

Using the Margules parameter of Fe-Mg subregular solution of mixing in garnet (Hackler and Wood 1989 and Berman 1990), the regular solution of Fe-Mg mixing in cordierite derived in this study and the K_D calculated from the experimental data, the equation (2) is rearranged as:

$$\ln K_D + \ln(\gamma_{Fe}/\gamma_{Mg})^{Gt} + \ln(\gamma_{Mg}/\gamma_{Fe})^{Crd} + (P-1)V^0_{1.298}/RT$$
$$= -\Delta H^0/RT + \Delta S^0/R. \tag{10}$$

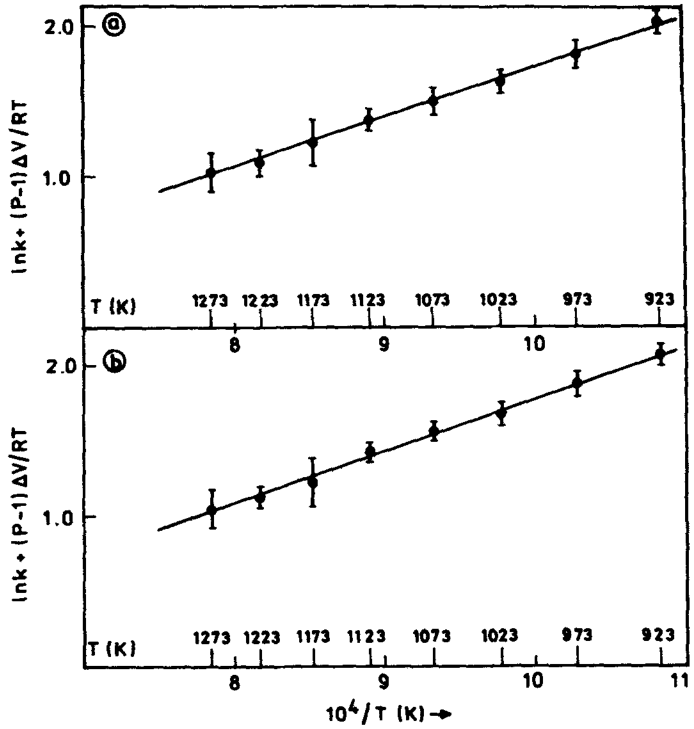

Figure 1(a and b). A plot of lnK (at 1 bar) + $(P-1)\Delta V^0_{1,298}/RT$ for reaction (1) versus $10^4/T$(K) of experimental data in the $P-T$ range 650 to 1050°C and 4 to 12 Kbar pressure for subregular mixing model of Hackler and Wood (1989) and Berman (1990) respectively. Solid circles with bar represent the mean and standard deviation of lnK at 1 bar.

Thus a plot of the left hand side of equation (10) versus $1/T$(K) yields a slope of $-\Delta H^0/RT$ and an intercept of $\Delta S^0/R$ from least square fit measurements (figures 1a and b). The derived values of ΔH^0 and ΔS^0 are $-6832(\pm 160)$, $-6920(\pm 169)$cal and $-3{\cdot}41(\pm 0{\cdot}047)$, $-3{\cdot}40(\pm 0{\cdot}046)$cal K^{-1}, respectively. The retrieved values of ΔH^0 and ΔS^0 of reaction (1) pass through the experimental bracket of all the above mentioned published experimental data (figures 1a and b).

The Fe-Mg relationship derived through equations (8) and (9) has been extended to include the effect of X_{Ca} and X_{Mn} in garnet on $\ln K_D - T$ relations. Thus, by taking the Ca-Mg binary as symmetric $W^{\text{Gt}}_{\text{Mg-Ca}} = W^{\text{Gt}}_{\text{Ca-Mg}} = 3300 - 1{\cdot}5\,T$ (Newton and Haselton 1981); the Ca-Fe and Fe-Mn binary to be ideal, Mg-Mn binary symmetric i.e., $W^{\text{Gt}}_{\text{Mg-Mn}} = 358$ cal per cation (Wood *et al* 1994); Fe-Mg binary as asymmetric (Hackler and Wood 1989), equation (11) is obtained:

$$\begin{aligned} RT\ln(\gamma_{\text{Fe}}/\gamma_{\text{Mg}})^{\text{Gt}} = {} & W_{\text{Fe-Mg}}X^2_{\text{Mg}} - W_{\text{Mg-Fe}}X^2_{\text{Fe}} + 2(W_{\text{Mg-Fe}} - W_{\text{Fe-Mg}})X_{\text{Fe}}X_{\text{Mg}} \\ & + 1/2(W_{\text{Mg-Fe}} + W_{\text{Fe-Mg}})(X_{\text{Ca}} + X_{\text{Mn}})(X_{\text{Mg}} - X_{\text{Fe}}) \\ & - W_{\text{Mg-Ca}}X_{\text{Ca}} - W_{\text{Mg-Mn}}X_{\text{Mn}}. \end{aligned} \tag{11}$$

Considering ternary (Fe-Mg-Ca) subregular mixing in garnet of Berman (1990) with additional term $W_{\mathrm{Mg-Mn}}$, the following equation is obtained:

$$\begin{aligned} RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}} = {} & W_{223}X_{\mathrm{Mg}}^2 - W_{233}X_{\mathrm{Fe}}^2 + 2(W_{233} - W_{223})X_{\mathrm{Fe}}X_{\mathrm{Mg}} \\ & + X_{\mathrm{Ca}}^2(W_{113} - W_{112}) + (W_{123} - 2W_{122})X_{\mathrm{Ca}}X_{\mathrm{Mg}} \\ & + (2W_{133} - W_{123})X_{\mathrm{Ca}}X_{\mathrm{Fe}} + W_{123}X_{\mathrm{Ca}}(X_{\mathrm{Mg}} - X_{\mathrm{Fe}}) \\ & - W_{\mathrm{Mg-Mn}}X_{\mathrm{Mn}}, \end{aligned} \tag{12}$$

where $W_{112} = 1718 - 1{\cdot}5T$; $W_{122} = 5513 - 1{\cdot}5T$; $W_{133} = 209 - 0.405T$; $W_{113} = 1619 - 0{\cdot}405T$; $W_{123} = 4687 - 1{\cdot}90T$, calories on one cation basis. W_V term of Berman (1990) has been ignored.

Combining equations (11), (12) and (7) with equation (3), the following geothermometric expression for the Mg-Fe exchange between garnet and cordierite is derived:

$$\begin{aligned} T(HW) = {} & 6832 + 0{\cdot}031(P-1) + 954(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} - A/RT\ln K_D \\ & + 3{\cdot}41 + 1{\cdot}23(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} + B, \\ A = {} & 166X_{\mathrm{Mg}}^2 - 506X_{\mathrm{Fe}}^2 + 680X_{\mathrm{Fe}}X_{\mathrm{Mg}} + 336(X_{\mathrm{Ca}} + X_{\mathrm{Mn}})(X_{\mathrm{Mg}} - X_{\mathrm{Fe}}) \\ & - 3300X_{\mathrm{Ca}} - 358X_{\mathrm{Mn}}B = 1{\cdot}5X_{\mathrm{Ca}}, \end{aligned} \tag{13}$$

$$\begin{aligned} T(\mathrm{Br}) = {} & 6920 + 0{\cdot}031(P-1) + 640(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} - C/RT\ln K_D \\ & + 3{\cdot}40 + 0{\cdot}78(X_{\mathrm{Fe}} - X_{\mathrm{Mg}})^{\mathrm{Crd}} + D, \\ C = {} & 18X_{\mathrm{Mg}}^2 - 296X_{\mathrm{Fe}}^2 + 556X_{\mathrm{Fe}}X_{\mathrm{Mg}} - 6339X_{\mathrm{Ca}}X_{\mathrm{Mg}} - 99X_{\mathrm{Ca}}^2 \\ & - 4269X_{\mathrm{Ca}}X_{\mathrm{Fe}} - 358X_{\mathrm{Mn}} + 4687X_{\mathrm{Ca}}(X_{\mathrm{Mg}} - X_{\mathrm{Fe}}). \\ D = {} & 1{\cdot}095X_{\mathrm{Ca}}^2 + 1{\cdot}1X_{\mathrm{Ca}}X_{\mathrm{Mg}} + 1{\cdot}09X_{\mathrm{Ca}}X_{\mathrm{Fe}} + 1{\cdot}90X_{\mathrm{Ca}}(X_{\mathrm{Mg}} - X_{\mathrm{Fe}}). \end{aligned} \tag{14}$$

where A and $C = RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}}$, W_H is related to Fe-Mg-Ca-Mn mixing in garnet; B and $D = RT\ln(\gamma_{\mathrm{Fe}}/\gamma_{\mathrm{Mg}})^{\mathrm{Gt}}$, $-W_S$ refers to Fe-Mg-Ca-Mn mixing in garnet; $K_D = (X_{\mathrm{Fe}}/X_{\mathrm{Mg}})^{\mathrm{Gt}}.(X_{\mathrm{Mg}}/X_{\mathrm{Fe}})^{\mathrm{Crd}}$;
$l = (\mathrm{Fe} + \mathrm{Mg} + \mathrm{Ca} + \mathrm{Mn})$; $X_{\mathrm{Mg}}^{\mathrm{Gt}} = \mathrm{Mg}/l$; $X_{\mathrm{Fe}}^{\mathrm{Gt}} = \mathrm{Fe}/l$; $X_{\mathrm{Ca}}^{\mathrm{Gt}} = \mathrm{Ca}/l$; $X_{\mathrm{Mn}}^{\mathrm{Gt}} = \mathrm{Mn}/l$;
$X_{\mathrm{Mg}}^{\mathrm{Crd}} = \mathrm{Mg}/\mathrm{Fe} + \mathrm{Mg}$; $X_{\mathrm{Fe}}^{\mathrm{Crd}} = \mathrm{Fe}/\mathrm{Fe} + \mathrm{Mg}$. The value of R is $1{\cdot}987\ \mathrm{cal\ K^{-1}}$. The numerical values given in the expressions of the geothermometers in equations (13) and (14) can be obtained in joules if multiplied by 4·184.

5. Application and accuracy of the geothermometer

The reformulated geothermometers have been applied to high-grade metamorphic rocks across a wide compositional range from different localities (South Central Maine, Osberg 1971; North East Bavaria, Okrusch 1971; Nain Complex, Berg 1971; Sonapahar, Lal *et al* 1978; Scottish caledonides, Ashworth and Chinner 1978; South India, Harris 1981; Finnish Lapland, Hörmann *et al* 1980; Ajitpura, Sharma and MacRae 1981 and Limpopo belt, Harris and Holland 1984). It is an improvement over the existing garnet-cordierite geothermometers, because these are derived from

Table 2. Comparison of the result obtained from present formulation T(HW) and T(Br) with other garnet-cordierite geothermometers.

S. No.	Rock type	Locality	Sample no.	aT	T_{Th}	T_P	T_B	$T_{A.P}$	T_{Ni}	T_{BS}	T(HW)	T(Br)
1.	Gt-crd-and-q	South Central Maine, n = 3	3a	550	541	544	642	543	480	670	587	586
2.			4c	550	549	550	655	550	486	685	593	592
3.			6a	550	542	544	649	544	480	677	587	586
				M.Std.	544 ± 4	546 ± 3	648 ± 5	545 ± 5	482 ± 3	677 ± 4	589 ± 3	588 ± 3
4.	Gt-crd-and/sil-q	North East Bavaria, n = 3	Sm6G	640	621	614	648	634	582	686	658	663
5.			Op170G	640	641	631	673	640	587	720	668	674
6.			Op157C	640	572	571	602	588	531	641	620	622
				M.Std.	611 ± 29	605 ± 25	641 ± 30	620 ± 23	566 ± 25	682 ± 25	648 ± 19	653 ± 20
7.	Crd-Hy-gt-sil	Limpopo Belt, n = 8	BB22a	670	653	642	650	649	572	656	655	662
8.			BB25C	670	704	685	667	687	615	675	700	705
9.			BB11d	670	734	712	724	722	663	698	730	737
10.			BB20a	670	725	703	709	724	660	719	723	737
				M.Std.	722 ± 38	701 ± 32	704 ± 35	714 ± 37	651 ± 45	706 ± 40	719 ± 30	728 ± 31
11.	Gt-crd-sil-q	North East Bavaria, n = 8	Op124G	680	682	667	688	685	641	732	704	711
12.			Sm27G	680	625	618	614	639	593	660	663	667
13.			Op146G	680	662	650	644	673	631	693	691	697
				M.Std.	649 ± 31	638 ± 27	645 ± 30	659 ± 27	614 ± 30	660 ± 32	680 ± 20	685 ± 21
14.	Ged-crd-gt-sil-q	Ajitpura Rajasthan n = 10	R	700	642	633	666	665	595	712	674	680
15.			9	700	719	699	737	719	663	780	727	734
16.			24	700	685	671	685	672	608	723	695	702
				M.Std.	662 ± 50	650 ± 43	702 ± 34	668 ± 40	604 ± 45	735 ± 38	682 ± 20	687 ± 20
17.	Gt-crd-sil-q	Sonapahar Assam, n = 2	734b	700	619	613	686	628	571	717	676	683
18.			81/684	700	676	662	704	673	623	733	702	705
				M.Std.	647 ± 29	637 ± 25	695 ± 9	650 ± 23	597 ± 26	725 ± 9	690 ± 10	694 ± 10

(*Continued*)

Table 2. (*Continued*)

S. No.	Rock type	Locality	Sample no.	aT	T_{Th}	T_P	T_B	$T_{A.P}$	T_{Ni}	T_{BS}	T(HW)	T(Br)
19.	Gt-crd-sil-q	Scottish	105765c	700	754	728	756	750	711	794	758	764
20.		Caledonides	10557c	700	718	698	758	734	680	786	731	746
21.		n = 10	187c	700	823	786	794	815	790	838	795	798
22.			190c	700	725	703	720	723	686	774	736	744
				M.Std.	726 ± 61	704 ± 52	737 ± 41	731 ± 50	689 ± 62	746 ± 42	737 ± 34	746 ± 35
23.	Gt-sp-crd-	South	1	740	703	684	693	706	641	713	720	724
24.	sil-q	India n = 2	2	740	710	690	697	712	648	720	722	726
				M.Std.	706 ± 4	687 ± 3	695 ± 1	709 ± 3	644 ± 4	716 ± 4	721 ± 1	725 ± 1
25.	Gt-crd-hy-q	Finnish	891	760	809	774	766	797	750	788	790	803
26.		Lapland	158I	760	761	735	749	750	697	771	755	762
27.		n = 4	161I	760	790	759	711	776	731	723	779	787
				M.Std.	806 ± 40	772 ± 31	761 ± 24	791 ± 33	745 ± 40	756 ± 35	789 ± 21	799 ± 21
28.	Gt-crd-hy-q	Nain	KI-355	770	875	827	776	860	861	784	843	857
29.		Complex	74-989	770	774	744	725	753	734	750	773	774
30.		n = 16	2-893	770	820	782	777	803	784	762	806	813
31.			2-1726	770	728	706	732	726	688	742	740	745
32.			2-1572	770	797	763	778	789	758	760	790	790
33.			2-4203	770	740	716	747	756	703	765	748	760
				M.Std.	805 ± 76	769 ± 62	770 ± 47	762 ± 62	766 ± 78	775 ± 51	794 ± 40	790 ± 41

All temperature computed at pressure inferred by respective authors. Where aT = Authors estimate of temperature °C. Prefix T in Th, p, etc., means temperature in °C for geothermometer given as (Th = Thompson 1976; P = Perchuk *et al* 1985; B = Bhattacharya *et al* 1988; A, P = Aranovich and Podlesskii 1989; Ni = Nichols *et al* 1992 and BS = Bhattacharya 1993). M.Std. is the mean and standard deviation of temperature in °C. Crd = cordierite, Gt = Garnet, Ged = gedrite, Hy = hypersthene, sil = sillimanite, Sp = spinel, q = quartz, n = number of data taken for calculation of temperature.

experimental data and are based on recent data on activity-composition relationship in (Fe-Mg-Ca-Mn) garnet solid solution. The error estimate in temperature for equations (13) and (14) is calculated by using the method of Chatterjee (1991, equations 9·66, p. 296 and 9·69, p. 296). Assuming 10% uncertainty in lnK values, uncertainty in the temperature estimates at 1000 K is ±40°C. A comparison of the temperature estimates (table 2) from this study $T(HW)$ (equation 13) and $T(\mathrm{Br})$ (equation 14) with those obtained from other calibrations (T_{Th}, Thompson 1976; T_{P}, Perchuk *et al* 1985; T_{B}, Bhattacharya *et al* 1988; $T_{\mathrm{A.P}}$, Aranovich and Podlesskii 1989; T_{Ni}, Nichols *et al* 1992; and T_{BS}, Bhattacharya 1993) reveals that (1) there is no compositional dependence in the temperature estimates with respect to garnet and cordierite solid solutions of the present study, (2) the standard deviation in the temperature estimates is lowest for $T(HW)$ and $T(\mathrm{Br})$ as compared to other calibrations and (3) the estimated temperature in the present study is consistent with temperature estimates of different authors using various geothermometers.

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References

Aranovich L Ya and Podlesskii K K 1983 The cordierite-garnet-sillimanite equilibrium: Experiments and applications. In *Kinetics and equilibrium in mineral reactions* (ed) S K Saxena (Berlin: Springer) pp. 173–198

Aranovich L Ya and Podlesskii K K 1989 Geothermobarometry of high-grade metapelites: Simultaneously operating reactions. In *Evolution of metamorphic belts;* (eds) J S R A Daly and B W D Yardley, Geological Society special publications **43** 45–61

Ashworth J R and Chinner G A 1978 Coexisting garnet and cordierite in migmatites from the Scottish Caledonides; *Contrib. Mineral. Petrol.* **65** 379–394

Berg J H 1971 Regional geobarometry in the contact aureoles of the anorthositic Nain Complex, Labrador; *J. Petrol* **18** 399–430

Berman R G 1988 Internally consistent thermodynamic data for minerals in the system Na_2O–K_2O–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–H_2O–CO_2; *J. Petrol* **29** 445–522.

Berman R G 1990 Mixing properties of Ca-Mg-Fe garnets; *Am. Mineral.* **75** 328–344

Bertrand P, Ellis D J and Green D H 1991 The stability of sapphirine-quartz and hypersthene-sillimanite-quartz assemblages: An experimental investigation in the system FeO-MgO-Al_2O_3-SiO_2 under H_2O and CO_2 conditions; *Contrib. Mineral. Petrol.* **108** 55–71

Bhattacharya A, Mazumdar A C and Sen S K 1988 Fe-Mg mixing in cordierite: Constraints from natural data and implications for cordierite-garnet geothermometry in granulites; *Am. Mineral.***73** 338–344

Bhattacharya S 1993 Refinement of geothermobarometry for cordierite granulites; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **102** 537–545

Chatterjee N D 1991 *Applied mineralogical thermodynamics* (Berlin: Springer-Verlag)

Ganguly J and Saxena S K 1984 Mixing properties of alumino-silicate garnets: Constraints from natural and experimental data and application to geothermo-barometry; *Am. Mineral* **69** 88–97

Hackler R T and Wood B J 1989 Experimental determination of Fe and Mg exchange between garnet and olivine and estimation of Fe-Mg mixing properties in garnet; *Am. Mineral.* **74** 994–999

Harris N 1981 The application of spinel-bearing metapelites to P-T determinations: An example from South India; *Contrib. Mineral. Petrol.* **76** 229–233

Harris N B W and Holland T J B 1984 The significance of cordierite-hypersthene assemblages from the Beitbridge region of the Central Limpopo belt: Evidence for rapid decompression in the Archean?; *Am. Mineral.* **69** 1030–1049

Hensen B J 1977 Cordierite-garnet bearing assemblages as geobarometers in granulite facies terrains; *Tectonophysics* **47** 73–88

Hensen B J and Green D H 1971 Experimental study of the stability of cordierite and garnet in pelitic compositions at high pressures and temperatures; *Contrib. Mineral. Petrol.* **33** 309–330

Holland T J B and Powell R 1990 An enlarged and updated internally consistent thermodynamic data set with uncertainties and correlations: The system K_2O-Na_2O-CaO-MgO-MnO-FeO-Fe_2O_3-Al_2O_3-TiO_2-SiO_2-C-H_2-O_2; *J. Metamor. Geol.* **8** 89–124

Hörmann P K, Raith M, Raase P, Ackermand D and Seifert F 1980 The granulites complex of Finnish Lapland: Petrology and metamorphic conditions in the Ivalojoki-Inarijarvi area; *Geological Survey of Finland Bulletin 308* **165** 1–96

Lal R K, Ackermand D, Seifert F and Haldar S K 1978 Chemographic relationship in sapphirine-bearing rocks from Sonapahar, Assam, India; *Contrib. Mineral. Petrol.* **67** 169–187

Newton R C and Haselton H T 1981 Thermodynamic of the garnet-plagioclase-Al_2SiO_5-quartz geobarometry. In *Thermodynamics of minerals and metals* (eds) R C Newton, A Navrostsky and B J Wood (Berlin: Springer-Verlag) 129–145

Nichols G T, Berry R F and Green H 1992 Internally consistent gehnitic-spinel-cordierite-garnet equilibria in the FMASHZn system: Geothermobarometry and applications; *Contrib. Mineral. Petrol.* **111** 362–377

Okrusch M 1971 Garnet-cordierite-biotite equilibria in the Steinach Aureole, Bavaria; *Contrib. Mineral. Petrol.* **32** 1–23

Osberg P H 1971 An equilibrium for Buchan type metamorphic rocks, South Central Maine; *Am. Mineral.* **56** 570–586

Perchuk L L and Lavrent'eva I V 1983 Experimental investigation of exchange equilibria in the system cordierite-garnet-biotite. In: *Kinetics and equilibrium in mineral reactions*; (eds) S K Saxena (Berlin: Springer) 199–239

Perchuk L L, Aranovich L Ya, Podlesskii K K and Lavrent'eva I V 1985 Precambrian granulites of the Alden shield, eastern Siberia USSR; *J. Metamo. Geol.* **3** 265–310

Sharma R S and MacRae N 1981 Paragenetic relation in gedrite-cordierite-staurolite-biotite-sillimanite-Kyanite gneisses at Ajitpura, Rajasthan, India; *Contrib. Mineral. Petrol.* **78** 48–60

Thompson A B 1976 Mineral reaction in pelitic rocks II: Calculation of some P-T-X (Fe-Mg) phase reactions; *Am. J. Sci.* **276** 425–454

Wood B J Hackler R T and Dobson D P 1994 Experimental determination of Mn-Mg mixing properties in garnet, olivine and oxide; *Contrib. Mineral. Petrol.* **115** 438–448