Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 100, No. 3, September 1991, pp. 281–291.

Coexisting pyroxenes from the basic granulites of Visakhapatnam area in the Eastern Ghats terrain

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MS received 11 August 1990; revised 13 May 1991

Abstract. Fifteen pairs of coexisting pyroxenes from basic granulites associated with leptynites in the khondalite suite of rocks are analysed and the distribution of Mg and Fe^{2+} ratios is presented. Temperature estimates for the coexisting pyroxenes from the basic granulites of Visakhapatnam may be expressed as 750 ± 100°C corresponding to intermediate pressure granulites.

Keywords. Coexisting pyroxenes; basic granulites; granulite terrain.

1. Introduction

Mineralogical thermometers and barometers have been widely used to estimate pressure and temperatures in high grade metamorphic rocks for various mineral assemblages.

Coexisting pyroxenes are believed to be important and interesting rock-forming minerals (Kretz 1982; Fonarev and Graphchicov 1987) which provide information on the physico chemical conditions. Pyroxene minerals are essential constituents in the basic granulites that occur in the Eastern Ghats granulite terrain (figure 1). The basic granulites are widespread and exposed in the leptynites of the khondalite suite of rocks in Visakhapatnam area, Andhra Pradesh. These are cofolded and inolved in the same deformation as those of leptynites and khondalites. Halden *et al* (1982) recognized four phases of deformation and three metamorphic events in the Eastern Ghats belt of Orissa. The regional structural set-up of Visakhapatnam showing folded and refolded structures and accompanying high grade and retrograde metamorphic mineral assemblages was reported by Sriramdas and Rao (1979). The corresponding ages of (2,600 my and 2,000 my: Rb–Sr method) metamorphism are inferred from the published data (Perraju *et al* 1979) in the Visakhapatnam region. The mafic granulites from Visakhapatnam district gave an Sm–Nd model age 2,860 my (Paul *et al* 1990) suggesting that the mafic granulites were intruded into the khondalite suite of rocks and subsequently involved in deformational and metamorphic episodes. The leptynites (garnetiferrous granites) associated with basic granulites in Visakhapatnam are characterized by garnet ± sillimanite-spinel assemblage and the *P–T* parameters correspond to 800°C ± 100°C/8 kbars (Rao and Rao 1987). The basic granulites are of gabbroic composition and clinopyroxene dominates over orthopyroxene. The

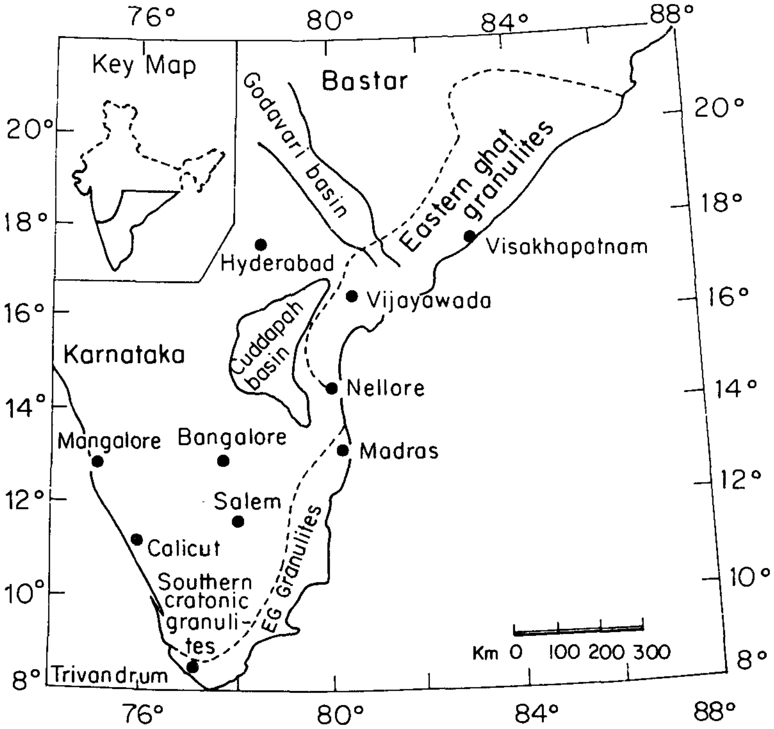

Figure 1. Map showing the extension of granulite belt in South India.

present study of coexisting pyroxenes attempts to establish temperature conditions of metamorphism in the area.

2. Chemical data

2.1 *Orthopyroxenes*

The data of the analysed orthopyroxenes (tabel 1), when referred to the diagram of Hess (1952) modified by Deer *et al* (1963), indicate that the orthopyroxenes range from hypersthene to ferrohypersthene in composition. The Al_2O_3 ranges between 1 and 3% by weight. When compared to the analyses reported earlier (Howie 1955; Leelanandam 1967), Al_2O_3 is relatively low. The amount of aluminium in the Z group is also variable and is always greater than that in the X group. This is a common observation in most of the orthopyroxenes of basic granulites.

2.2 *Clinopyroxenes*

The data of the analysed clinopyroxenes (table 2) when extrapolated in the diagram of Hess (1949) and later slightly modified by Muir (1951), indicate that clinopyroxenes fell in the salite and augite fields (figure 2).

Table 1. Microprobe analyses and structural formulae of orthopyroxenes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	52·05	51·58	50·68	50·36	50·12	50·04	49·06	52·04	52·33	51·05	51·75	51·66	51·36	51·66	50·58
TiO_2	0·72	0·48	0·62	0·46	0·14	0·52	0·62	0·08	0·05	0·09	0·12	0·06	0·08	0·11	0·08
Al_2O_3	2·76	2·86	2·86	1·98	1·28	1·83	2·06	1·63	0·96	1·43	1·49	1·54	1·85	1·40	1·07
Cr_2O_3	—	—	—	—	—	—	—	0·03	0·03	0·01	0·09	0·05	0·01	0·01	—
FeO	18·51	24·35	23·70	27·64	32·55	30·73	31·92	22·49	23·18	24·21	23·39	25·16	24·86	24·04	29·42
MnO	0·43	0·38	0·43	0·11	0·39	0·31	0·52	0·64	0·64	1·32	0·45	0·53	0·68	0·57	0·71
MgO	24·26	19·93	20·24	18·33	15·04	15·44	14·71	22·01	22·93	21·14	22·99	21·47	20·22	21·68	17·97
CaO	0·62	0·48	0·53	0·42	0·27	0·29	0·45	0·52	0·43	0·62	0·60	0·55	0·57	0·62	0·77
Na_2O	0·12	0·20	0·17	0·16	0·09	0·17	0·12	—	0·03	0·04	—	0·07	0·03	—	—
K_2O	0·09	0·10	0·10	0·08	0·06	0·09	0·06	0·09	—	0·01	0·01	—	—	—	—
Total	99·86	99·70	99·63	99·54	99·94	99·52	99·52	99·50	100·58	99·92	100·89	101·10	99·67	100·09	100·60
	Number of ions on the basis of 6 oxygens														
Si_{IV}	1·915	1·950	1·917	1·932	1·964	1·954	1·931	1·951	1·948	1·933	1·923	1·932	1·946	1·941	1·945
Al_{IV}	0·085	0·050	0·083	0·068	0·036	0·046	0·069	0·049	0·042	0·064	0·065	0·068	0·054	0·059	0·048
Al	0·035	0·077	0·044	0·021	0·023	0·038	0·026	0·023	—	—	—	—	0·028	0·003	—
Fe	0·567	0·767	0·747	0·884	1·063	1·000	1·047	0·703	0·719	0·764	0·725	0·784	0·785	0·753	0·943
Mn	0·013	0·012	0·014	0·013	0·013	0·010	0·017	0·020	0·020	0·042	0·014	0·017	0·022	0·018	0·023
Mg	1·339	1·073	1·149	1·055	0·884	0·904	0·868	1·238	1·280	1·201	1·282	1·204	1·149	1·222	1·037
Ca	0·024	0·019	0·021	0·017	0·011	0·012	0·019	0·021	0·017	0·025	0·024	0·022	0·023	0·025	0·032
Na	0·008	0·015	0·012	0·012	0·007	0·012	0·009	—	0·002	0·003	—	0·005	0·002	—	—
K	0·004	0·005	0·005	0·004	0·002	0·005	0·003	0·004	—	0·001	—	—	—	—	—
Ti	0·026	0·014	0·017	0·013	0·003	0·015	0·018	0·009	0·001	0·002	0·003	0·001	0·002	0·003	0·001
Cr	—	—	—	—	—	—	—	0·001	0·001	—	0·003	0·001	—	—	—

Location of samples: 1) Meterological Observatory, 2) Peda Waltair, 3) Peda Waltair (around P.V.G. Raju Bunglow), 4) Governor's Bunglow, 5) Around T.B. Hospital, 6) Siripuram junction, 7) Maddilapalem, 8) Madasaralove, 9) Gopalapatnam junction, 10) Madhurawada, 11) Pendurti, 12) Gopalapatnam, 13) Madhurawada, 14) Gajuvaka and 15) Gajuvaka.

Table 2. Microprobe* analyses and structural formulae of clinopyroxenes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	50·56	50·78	50·88	51·04	48·08	50·26	49·88	52·04	51·87	50·24	51·53	51·80	50·74	51·23	50·35
TiO_2	0·42	0·58	0·18	0·52	0·30	0·32	0·36	0·27	0·18	0·24	0·34	0·20	0·24	0·30	0·21
Al_2O_3	4·12	3·26	3·53	2·97	4·38	2·35	3·02	2·72	2·02	2·44	2·51	2·29	2·20	2·68	2·03
Cr_2O_3	—	—	—	—	0·05	—	—	0·03	0·08	0·05	0·16	0·08	—	0·01	0·01
FeO	8·00	10·74	10·98	12·76	15·28	14·75	15·35	8·50	8·50	10·13	8·24	10·35	9·58	9·53	12·01
MnO	0·32	0·33	0·13	0·36	0·27	0·49	0·32	0·22	0·25	0·52	0·21	0·24	0·31	0·27	0·32
MgO	14·63	13·40	12·98	12·18	10·44	11·15	10·93	14·02	13·92	13·32	14·23	14·11	13·26	13·67	11·93
CaO	20·39	19·95	19·48	19·42	18·62	19·89	19·04	22·30	22·17	21·51	22·74	21·41	22·20	21·64	21·13
Na_2O	0·35	0·27	0·46	0·27	0·36	0·24	0·38	0·52	0·46	0·23	0·36	0·06	0·30	0·36	0·29
K_2O	0·14	0·08	0·31	0·12	0·12	0·09	0·14	—	—	—	—	0·02	—	—	0·01
Total	98·93	99·39	98·93	99·64	99·20	99·65	99·56	100·62	99·45	99·68	100·32	100·56	98·82	99·69	98·29
Number of ions on the basis of 6 oxygens															
Si_{IV}	1·894	1·914	1·926	1·933	1·895	1·931	1·918	1·927	1·945	1·916	1·917	1·930	1·927	1·922	1·940
Al_{IV}	0·106	0·086	0·074	0·067	0·105	0·069	0·082	0·073	0·055	0·084	0·083	0·070	0·073	0·078	0·060
Al	0·076	0·059	0·083	0·065	0·094	0·037	0·055	0·046	0·034	0·025	0·027	0·030	0·025	0·041	0·032
Fe	0·250	0·337	0·346	0·403	0·492	0·472	0·492	0·248	0·265	0·322	0·255	0·321	0·303	0·298	0·386
Mn	0·010	0·010	0·004	0·012	0·009	0·016	0·010	0·007	0·008	0·016	0·007	0·008	0·010	0·009	0·010
Mg	0·822	0·758	0·737	0·691	0·605	0·643	0·630	0·779	0·783	0·762	0·794	0·788	0·755	0·769	0·689
Ca	0·818	0·806	0·790	0·788	0·771	0·891	0·785	0·885	0·891	0·879	0·907	0·855	0·903	0·870	0·872
Na	0·025	0·019	0·033	0·020	0·027	0·018	0·028	0·037	0·033	0·017	0·026	0·004	0·022	0·027	0·022
K	0·007	0·001	0·015	0·006	0·006	0·005	0·007	—	—	—	—	0·001	—	—	—
Ti	0·012	0·016	0·005	0·015	0·008	0·009	0·010	0·007	0·005	0·007	0·009	0·006	0·007	0·008	0·006
Cr	—	—	—	—	0·001	—	—	0·001	0·002	0·001	0·004	0·002	—	—	—

Description of the samples are same as in Table 1

*The data was collected by A T Rao during the UNESCO trip to USA using the ARL Model Electron-probe at Chicago University. The quantitative analyses were done at 15 kilovolts, on polished thin sections coated with a layer of carbon several hundred Å thick. The Gore Mountain Garnet and a basalt glass were used as the standards. Duplicate analysis of standard confirmed the values given with an accuracy of ± 5%.

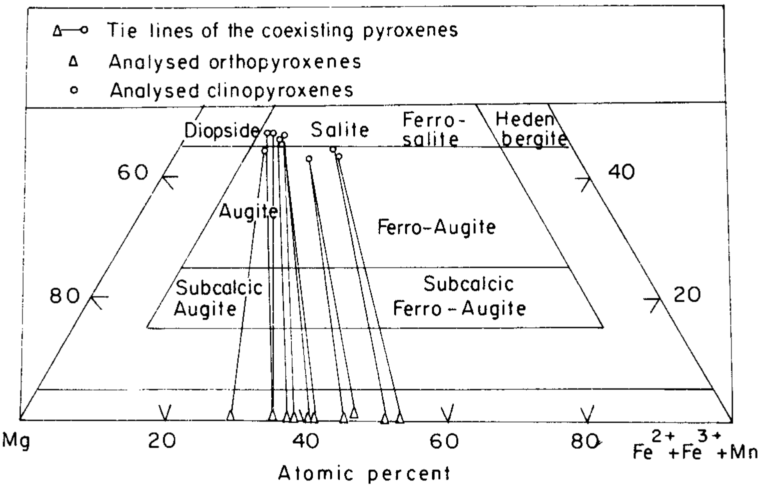

Figure 2. Distribution of pyroxene analysis with respect to Ca, Mg and $Fe^{2+} + Fe^{3+} + Mn$ atomic percentages (after Deer *et al* 1963).

3. Distribution of Mg and Fe^{2+} among coexisting pyroxenes

Mueller (1960) and Kretz (1961) concluded that ortho- and clino-pyroxenes behave as ideal solid solutions with respect to Mg and Fe^{2+} and the distribution coefficient (K_D) is defined by the following equation:

$$K_D = \frac{X^{Opx}Mg}{1 - X^{Opx}Mg} \times \frac{1 - X^{Cpx}Mg}{X^{Cpx}Mg}$$

where

$$X^{Opx}Mg = Mg/Mg + Fe^{2+} \text{in Opx and}$$

$$X^{Cpx}Mg = Mg/Mg + Fe^{2+} \text{in Cpx}$$

In recent years the study of distribution of Mg and Fe^{2+} among coexisting silicate minerals has attained considerable importance, though ortho- and clino-pyroxenes were studied in detail. Kretz (1961, 1963) demonstrated that the distribution coefficient (K_D) relating to Mg and Fe^{2+} distribution between coexisting ortho- and clino-pyroxenes differs between igneous and metamorphic assemblages. Though Bartholome (1962) considered the Mg and Fe^{2+} partition coefficient K_p in a manner opposite to that of Kretz, the K_p values obtained are different for both igneous and metamorphic mineral assemblages.

$$K_p = \frac{(F^{2+}/Mg)\ Ca - poor}{(Fe^{2+}/Mg)\ Ca - rich}$$

The Ca, Mg, Fe^{2+} and K_p values for coexisting pyroxene pairs are given in table 3. The k_p values mostly range from 1·5 to 2·0. The K_p values for coexisting pyroxenes (Leelanandam 1967) from charnockite series of Madras and Kondapalli range from 1·7 to 2·3. The Fe^{2+}/Mg values of the ortho- and clino-pyroxenes are plotted in the diagram (figure 3) of Bartholome (1962). The values show clustering along the partition coefficient line K_p 1·8, indicative of metamorphic mineral assemblage.

Table 3. Ca, Mg, Fe^{2+}*, K_p and K_D values for coexisting pyroxenes.

Orthopyroxene			Clinopyroxene							°C from solvus			°C from
Fe	Mg	Ca	Fe	Mg	Ca	X^{Opx}	X^{Cpx}	Ca	K_p	Low T	High T	K_D	K_D
0·561	1·339	0·024	0·219	0·822	0·818	0·295	0·210	0·440	1·572	937	1008	1·574	905
0·754	1·073	0·019	0·323	0·758	0·806	0·412	0·298	0·427	1·649	946	1012	1·650	850
0·730	1·149	0·021	0·302	0·737	0·790	0·388	0·290	0·432	1·550	921	1001	1·552	923
0·851	1·055	0·017	0·395	0·691	0·788	0·446	0·363	0·420	1·411	929	1004	1·413	1055
1·042	0·884	0·011	0·471	0·605	0·771	0·541	0·437	0·417	1·514	882	983	1·518	951
0·985	0·904	0·012	0·440	0·643	0·819	0·521	0·406	0·430	1·592	840	962	1·591	892
1·031	0·868	0·019	0·457	0·630	0·785	0·543	0·420	0·419	1·637	886	984	1·640	857
0·696	1·238	0·021	0·199	0·729	0·885	0·359	0·203	0·474	2·200	657	861	2·199	604
0·697	1·280	0·017	0·223	0·783	0·891	0·353	0·221	0·469	1·912	694	884	1·923	702
0·701	1·201	0·025	0·299	0·762	0·879	0·369	0·282	0·453	1·487	786	934	1·489	978
0·669	1·282	0·024	0·195	0·794	0·907	0·342	0·205	0·478	2·124	613	835	2·015	664
0·714	1·204	0·022	0·291	0·788	0·855	0·372	0·269	0·442	1·606	873	978	1·609	879
0·716	1·149	0·023	0·247	0·755	0·903	0·384	0·246	0·474	1·905	634	848	1·910	707
0·706	1·222	0·025	0·250	0·769	0·870	0·366	0·245	0·460	1·777	757	919	1·779	772
0·897	1·037	0·032	0·376	0·689	0·872	0·464	0·353	0·450	1·585	759	920	1·586	896

* Fe^{2+} was calculated based on stoichiometry

$X^{Opx} = Fe^{2+}/(Mg + Fe^{2+})$ in orthopyroxene: $X^{Cpx} = Fe^{2+}/(Mg + Fe^{2+})$ in clinopyroxene;

Ca = Ca/(Ca + Mg + Fe^{2+}) in clinopyroxene; $K_p = (Fe^{2+}/Mg)_{Opx}/(Fe^{2+}/Mg)_{Cpx}$:

$K_D = X^{Opx/1} - x^{Opx/x^{Cpx}}/1 - x^{Cpx}$; °C from $K_D = T = 1130/(\ln K_D + 0{\cdot}505)$

Low $T = 1080$°C: $T = 1000/(0{\cdot}054 + 0{\cdot}608\,X^{Cpx} - 0{\cdot}304\ \text{in}\ (1 - 2[\text{Ca}]))$; whereas T is absolute temperature.

High $T = 1080$°C: $T = 1000/(0{\cdot}468 + 0{\cdot}246\,X^{Cpx} - 0{\cdot}123\ \text{in}\ (1 - 2\,[\text{Ca}]))$; Therefore $T - 273 =$ °C

Description of the samples 1–15 are the same as in table.

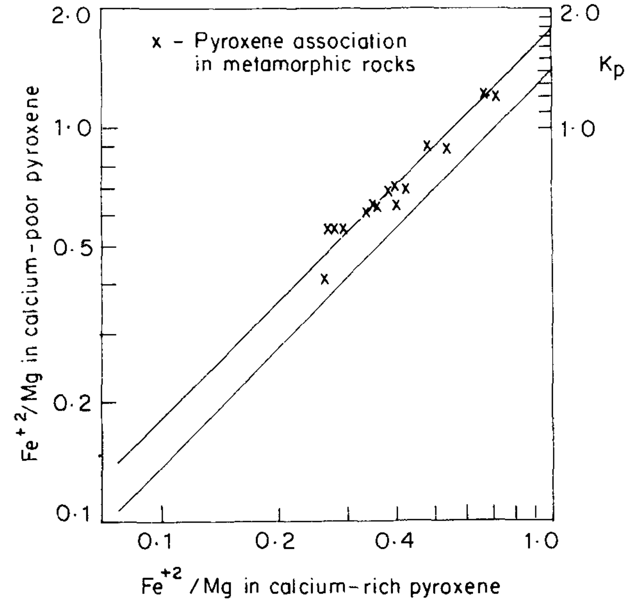

Figure 3. Graphical log-log plot indicating the distribution of Fe^{2+}/Mg in coexisting pyroxenes (after Bartholome 1962).

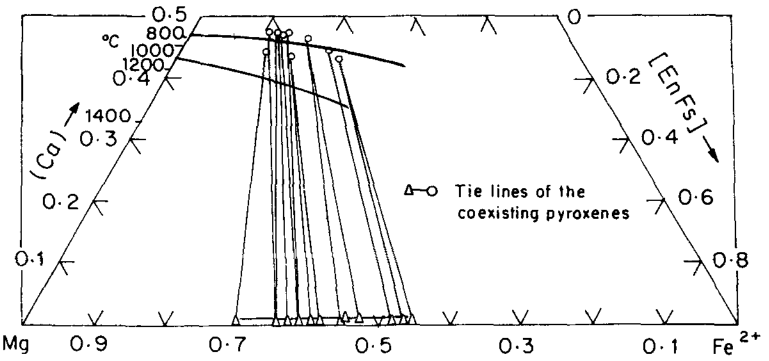

Figure 4. The pyroxene quadrilateral showing associated Ca-rich and Ca-poor pyroxenes from the Visakhapatnam region (after Kretz 1982).

Recent study by Kretz (1982) is found to be much useful in determining the refined distribution coefficient K_D and also in establishing the temperature conditions. The Ca, Mg, Fe^{2+} and K_D values along with the deduced temperatures (figures 4 and 5) for the coexisting pyroxenes in the pyroxene granulites are given in table 3. The clinopyroxenes indicate lower temperature (figure 6), perhaps corresponding to the reset values during retrograde metamorphism. The P–T conditions are calculated based on the results of Wood and Banno (1973), Wells (1977), Powell (1978), Bertrand and Mercier (1985) and Fonarev and Graphchicov (1987) and are given in table 4. The data obtained from the methods of Kretz (1982), Wood and Banno (1973), Wells (1977) and Bertrand and Mercier (1985) range from 700–1000°C and gave a mean temperature of 850°C with an uncertainty in these numbers estimated to be ± 150°C.

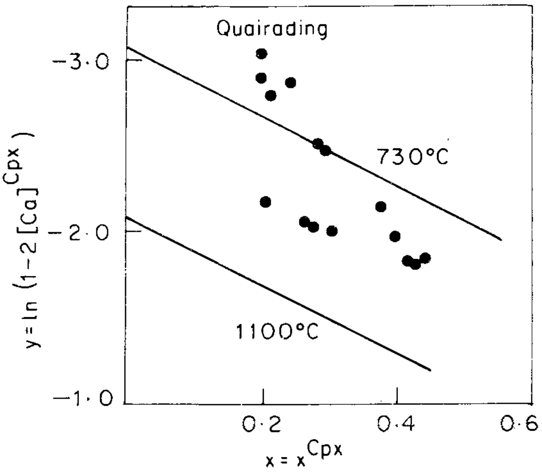

Figure 5. Plot of ln $(1-2\mathrm{Ca}^{\mathrm{Cpx}})$ *vs.* X^{Cpx} for pyroxenes from Visakhapatnam region (after Kretz 1982).

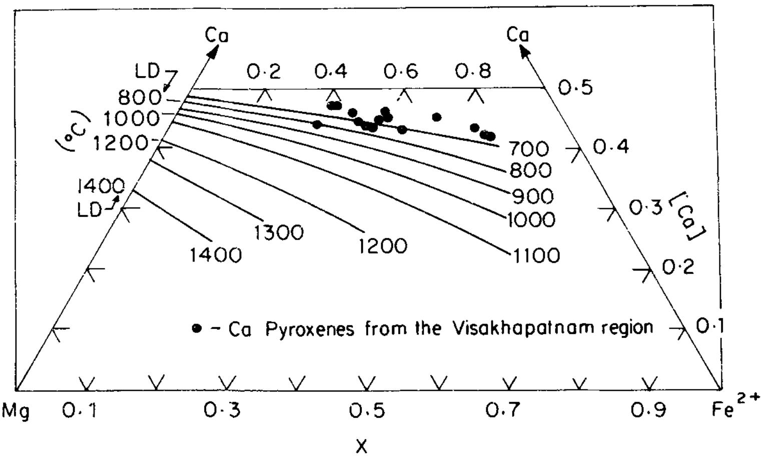

Figure 6. The pyroxene quadrilateral, showing (°C) on the Ca pyroxene slope of the solvus surface (after Kretz 1982).

The other methods of Powell (1978) and Fonarev and Graphchicov (1987) indicate a lower temperature of 750°C ± 100°C. Lindsley (1983) reported that the application of his method of pyroxene thermometry to granulites has difficulties but the coexisting pyroxene pairs under study have yielded a range of 600 to 800°C using the isothermal, isobaric projections of phase equilibria on the pyroxene quadrilateral (Davidson and Lindsley 1989). The mineralogical thermometers are formulated on the main principle of redistribution of components between coexisting minerals involving experimental studies and modelling of mineral equilibria of solid solutions. However, the accuracy of calibration of thermometers depends more on the reconstruction of primary pyroxene compositions on the basis of textural evidence. The temperature of 750 ± 100°C obtained by the calculations of pyroxene

Table 4. Estimate of pressure annd temperature values of coexisting pyroxenes.

Method/	Bertrand and Mercier (1985)		Fonarev and Graphchicov (1987)		Powell (1978)		Wood and Banno (1973)	Wells (1977)
Sample No.	$P(K)$ bar	T(°C)	$P(K)$ bar	T(°C)	$P(K)$ bar	T(°C)	T(°C)	T(°C)
1	4·000	898	4·000	815	4·000	827	963	993
	6·000	899	6·000	820	6·000	834		
	8·000	900	8·000	826	8·000	841		
2	4·000	875	4·000	765	4·000	766	925	995
	6·000	877	6·000	768	6·000	773		
	8·000	877	8·000	771	8·000	781		
3	4·000	876	4·000	828	4·000	770	921	984
	6·000	877	6·000	832	6·000	778		
	8·000	878	8·000	837	8·000	786		
4	4·000	867	4·000	795	4·000	716	894	967
	6·000	868	6·000	798	6·000	724		
	8·000	869	8·000	801	8·000	732		
5	4·000	825	4·000	773	4·000	641	869	951
	6·000	825	6·000	775	6·000	648		
	8·000	826	8·000	776	8·000	655		
6	4·000	788	4·000	758	4·000	676	861	934
	6·000	789	6·000	760	6·000	682		
	8·000	789	8·000	761	8·000	687		
7	4·000	823	4·000	762	4·000	734	875	960
	6·000	823	6·000	764	6·000	742		
	8·000	824	8·000	766	8·000	784		
8	4·000	703	4·000	683	4·000	780	843	854
	6·000	703	6·000	786	6·000	782		
	8·000	704	8·000	688	8·000	784		
9	4·000	696	4·000	689	4·000	742	832	837
	6·000	697	6·000	692	6·000	744		
	8·000	698	8·000	694	8·000	746		
10	4·000	738	4·000	744	4·000	828	851	876
	6·000	739	6·000	747	6·000	831		
	8·000	739	8·000	750	8·000	834		
11	4·000	677	4·000	665	4·000	797	824	827
	6·000	678	6·000	668	6·000	799		
	8·000	679	8·000	670	8·000	800		
12	4·000	818	4·000	730	4·000	815	899	950
	6·000	819	6·000	733	6·000	820		
	8·000	820	8·000	736	8·000	825		
13	4·000	674	4·000	682	4·000	797	818	835
	6·000	675	6·000	685	6·000	798		
	8·000	676	8·000	687	8·000	800		
14	4·000	749	4·000	719	4·000	825	863	890
	6·000	750	6·000	721	6·000	825		
	8·000	751	8·000	724	8·000	831		
15	4·000	672	4·000	715	4·000	848	802	833
	6·000	673	6·000	717	6·000	850		
	8·000	673	8·000	719	8·000	852		

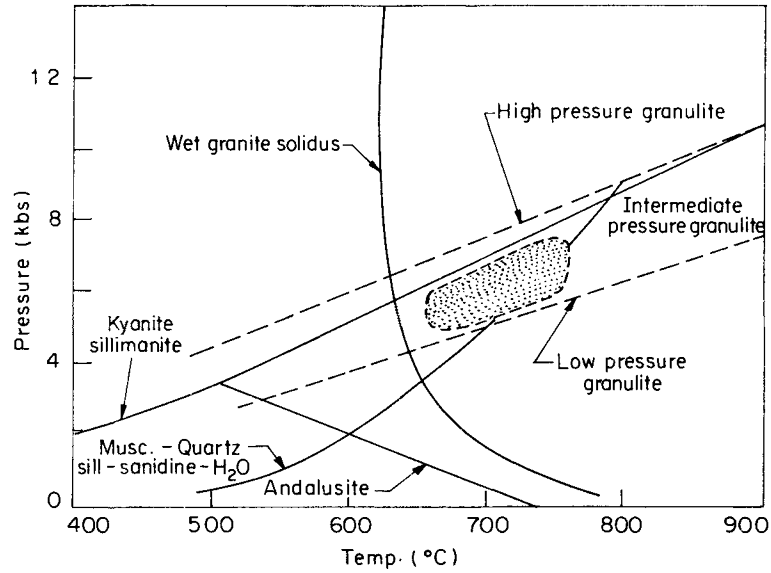

Figure 7. The stippled field indicates the estimated P/T conditions of equilibration of the S.E. Sri Lanka granulites (after Jayawardena and Carswell 1976).

geothermometers given by Powell (1978) and Fonarev and Graphchicov (1987) is preferred because of the overall consistency of the values (table 4).

Similarities in mineralogy and petrology among basic granulites of the Eastern Ghats granulite belt and granulites of Sri Lanka reflect, in general, similar conditions of crystallization of pyroxenes. The regional extension of granulite belt in India and Sri Lanka (Yoshida *et al* 1990) indicates that the coexisting pyroxenes in basic granulites have attained equilibrium under P–T environment corresponding to intermediate pressure granulites (figure 7).

Acknowledgements

The authors are grateful to Prof. V I Fonarev of the Institute of Experimental Mineralogy for furnishing the computer-processed P–T data. JUR, AMR and PCSR thank the Council of Scientific and Industrial Research and University Grants Commission, New Delhi for financial assistance.

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