Reaction Textures in Calc-Silicates as Guides to the Pressure – Temperature – Fluid History of Granulite Facies Terrains in East Gondwana

M. Satish-Kumar*, M. Santosh*,** and M. Yoshida*

(with 9 Figures and 2 Tables)

Abstract

Calc-silicate mineral assemblages are important monitors in pressure-temperature-fluid histories of granulite facies terrains.   In this contribution, common mineral reactions and textures preserved by the calc-silicates and marbles in the East Gondwana terrains are reviewed in the light of newly acquired thermodynamic information.   Reaction textures involving wollastonite and scapolite are of considerable interest as they provide information on the post-peak metamorphic history of the terrain.   Wollastonite-scapolite with rare, grossular-bearing calc-silicate assemblages occur in the Kerala Khondalite Belt.   These mineral assemblages are indicative of a low X_{CO_2} fluid composition during peak metamorphism.   Also it is noticed that these lithologies show retrograde reaction textures which are characteristic of post-peak metamorphic carbonic fluid infiltration.   The calc-silicates in the Eastern Ghats, India and Prydz Bay and Rauer group of East Antarctica typically show these reaction textures, with a high pressure-temperature metamorphic history and near isothermal uplift.   The mineral assemblages in calc-silicates of southern India, Sri Lanka and Lützow-Holm Bay, East Antarctica, have equlibrated at lower pressure-temperature conditions, with an internally controlled fluid regime in the peak metamorphic event.   The retrogression textures shown by the calc-silicates from these terrains indicate a post-peak metamorphic carbonic fluid infiltration, probably during isothermal decompression.

Key words: Calc-silicates, Kerala Khondalite Belt, East Gondwana, Scapolite, Wollastonite.

1. Introduction

The earth's deep crust is considered to be predominantly granulitic.   Hence, granulite facies terrains are of fundamental importance in understanding the early crustal evolutionary history of the Earth and of continental geodynamics.   Investigations on the high-grade rocks exposed now in the stable continental shield areas provide information on the tectonic history of the region, and also on the processes going on in the deeper parts of the earth's crust.   The focus of granulite studies have been from different angles, of which thermobarometry, geochemistry, geochronology, nature and role of fluids, and tectonic modelling are among the important themes (e.g., Bohlen, 1987).   Many of the granulite terrains are supposed to have an original crustal thicknesses of more than 50 km, as the now exposed portion is almost eroded up to 25 km, and it is estimated that a similar thickness extends below.   For attaining such large dimensions

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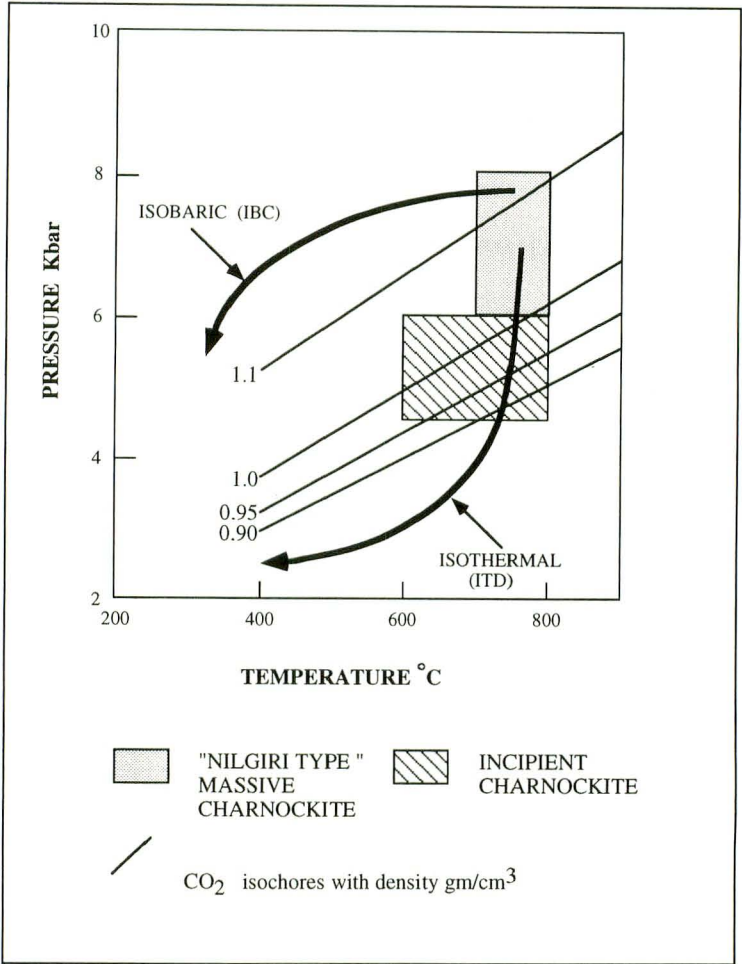
Fig. 1. Schematic pressure-temperature diagram showing ideal P-T evolution of granulites, namely, isothermal decompression path (ITD) and isobaric cooling path (IBC) (modified after Santosh 1992)

of crustal thickness, the most suitable model proposed is continent-continent collision (NEWTON and PERKINS, 1982; DRURY *et al.*, 1984).   However, recent models do not completely endorse this, as the formation of granulites needs anomalous thermal gradients which can only be supplied through magma underthrusting (BOHLEN, 1987).   Therefore, models of granulite genesis critically depend on the pressure-temperature information provided mainly by the coexisting mineral assemblages (BOHLEN, 1987; ELLIS, 1987; HARLEY, 1987).   Recent developments in determining the absolute thermobarometry (e.g., FITZIMONS and HARLEY, 1994) have paved the way for a better understanding of granulite genesis (SPEAR, 1992 and references therein).   Most of the granulite terrains show peak metamorphic pressure-temperature (P-T) conditions clustering around 700-800°C and 6.5-9 Kbar (NEWTON and PERKINS, 1982; BOHLEN, 1987).   HARLEY (1989),

based on the data from a large number of granulite terrains, illustrated that there is no such clustering, and showed that granulite facies assemblages can stabilize under a wide range of P-T conditions. Granulite formation and evolution can be complemented by different earth processes. The P-T evolution of granulites provides important clues on the evolution of the earth's crust through its history. Fig. 1 shows the two different evolutionary paths of granulite after attaining the peak P-T conditions, viz., isothermal decompression(ITD) and isobaric cooling (IBC). ITD granulites are assumed to have formed due to crustal thickening with a magmatic heat source, whereas one of the important processes in the formation of IBC granulites can be magmatic accretion with or without crustal extension (HARLEY, 1989). The role of fluids in deep crustal processes has been a topic of continuous debate. One of the popular models invokes pervasive CO_2 influx at the base of the crust (NEWTON *et al.*, 1980), and other models propose vapour-absent metamorphism (LAMB and VALLEY, 1984) and also partial-melt segregation to generate granulites. In evaluating the fluid processes associated with granulite genesis, calc-silicates in the granulite terrains have recently assumed importance.

Calc-silicates and marbles have been the context of many studies relating to contact metamorphism and fluid infiltration. Metacarbonate rocks are more sensitive than other rock types to the changes in fluid composition which can result in various dehydration / decarbonation / hydration / carbonation reactions which are recorded as mineralogical and chemical changes (FERRY 1986, 1988, 1992). Apart from this, phase equilibria of metacarbonates are useful tools, since they can preserve the changes that affect post-metamorphic evolutionary history of the terrain. Calc-silicate assemblages in regionally metamorphosed terrains have been rarely used in evaluating the P-T conditions and evolution of the high-grade terrains in the past decade (VALLEY and ESSENE, 1980; SCHENK, 1984; HARLEY, 1987; WARREN *et al.*, 1987; MOTOYOSHI *et al.*, 1991). The reasons for lack of attention is the paucity of calc-silicates in high grade terrains and the lack of appropriate thermodynamic data. With the aid of new information on the phase equilibria of granulite facies calc-silicate assemblages, and the recognition of wollastonite-scapolite assemblages in many regional terrains, recent studies have focussed on the evaluation of pressure-temperature- fluid histories in granulite-facies calc-silicates (HARLEY and BUICK, 1992; PETERS and WICKHAM, 1994; HOEFFBAUER and SPIERING, 1994; HARLEY *et al.*, 1994). Table 1 summarises some of the salient features of the calc-silicate occurrences reported from various granulite terrains.

Even though the wollastonite stability relation with fluid composition had been experimentally proved decades back (GREENWOOD, 1967), only recently has the importance of wollastonite been seen for vapor-free granulite genesis(LAMB and VALLEY, 1984; LAMB *et al.*, 1987). Further, the fact that granulite-facies calc-silicate assemblages are controlled by an internal fluid composition has also been cited against pervasive influx of fluids in granulite terrains (e.g., OLIVER *et al.*, 1992). The reaction textures usually preserved in calc-silicates provide vital clues in the post metamorphic P-T evolution of the terrain. They can also provide the fluid compositions prevailing at and after the peak

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Table 1.　Review of the Salient Features of Calc-silicates Reported from Granulite Terrains

Serial No.	Location	Characteristic mineral assemblages	Regional P-T condition	P-T trajectory	Reference
1	Rauer Group East Antarctica	(a) Wol+Scp+Grt+Cpx+ Cc+Qtz (b) Scp+Cpx+Qtz±Cc (c) Grt +Scp+Cc+Qtz	840 ± 40°C 7-9 Kbar	Near isothermal decompression	Harley and Buick, 1992
2	Prydz Bay East Antarctica	Wol+Scp+Plg+Grt +Cpx	775 ± 50°C 6Kbar	Clockwise decompression	Motoyoshi et al., 1991
3	Lutzow-Holm Bay East Antarctica	(a) Ep+Grt+Cpx+Amph+ Plg+Scp+Sph+Cc+Qtz (b) Wol+Grt+Cpx+Amph+ Scp±Sph±Cc±Qtz	810 ± 20°C 7 Kbar	Not discussed	Hiroi et al., 1987
4	Arunta Block Australia	Scp+Wol+Cc+Cpx+ Grt+Sph	850-920°C 8±1 Kbar	Isobaric cooling	Warren et al., 1987
5	Calabria Italy	(a) Scp+Cpx+Plg+Kfld± Phl±Cc±Qtz (b)Dol+Cc+Fo+Sp+Amph+ Phl±Scp±Cpx	800°C 7-8 Kbar	Initially isothermal followed by isobaric cooling	Schenk, 1984
6	Eastern Ghats India	(a) Cc+Qtz+Scp+Plg+Cpx+ Kfld+Sph (b) Cc+Scp+Wol+Grt+ Cpx+Sph+Kfld (c) Cc+Qtz+Wol+Scp+ Grt+Cpx+Sph+Kfld	950°C 9±1Kbar	Initially isobaric followed by isothermal	Shivaprakash, 1981; Dasgupta, 1993
7	Highland Complex SriLanka	(a) Cc+Dol+Phl±Fo±Cpx± Spx±Amph±Gr±Po (b) Cpx+Scp+Sph+Kfld± Plg±Qtz±Phl±Gr±Po (c) Wol+Cpx+Scp+Sph±Cc± Kfld±Plg±Qtz±Gr±Po	750-900°C 8Kbar	Isothermal cooling	Hoeffbauer and Spiering,1994; Hippurachi, 1968
8	Nevada U. S. A	(a) Dol+Cc+Bt+Cpx+Qtz+ Ru±Scp±Kfld±Amph (b) Cc+Bt+Plg+Cpx+Qtz+ Sph±Scp±Kfld (c) Cc+Cpx+Plg+Qtz+Sph+ Scp±Kfld	600-750°C 6 Kbar	Initially isobaric followed by isothermal	Peters and Wickham, 1994
9	Adirondacks USA	(a) Phl+Cc+Qtz+Amph+ Kfld+Cpx (b) Phl+Cc+Qtz+Cpx	750°C 8±1 Kbar	Isothermal decompression	Valley and Essene, 1980
10	Waits River Formation U. S. A	(a) Ank+Cc+Qtz+Mus+ Ru+Gr (b) Bt+Mus+Ank+Cc+Qtz+ Plg+Ru+Gr±Chl (c)Amph+Bt+Chl+Cc+Qtz+ Plg+Rut+Sph+Gr±Ank±Clzo (d) Cpx+Kfld+Cc+Qtz+ Plg+Clzo+Sph+Gr	480-573°C 7±1.5 Kbar	Not discussed	Ferry, 1992
11	Kerala Khondalite Belt India	(a) Cpx+Qtz+Kfld+Plg± Sph±Cc (b) Cpx+Wol+Scp+Kfld+ Cc+Plg+Qtz+±phl±Amph± Sph±Gr	700±50°C 5±1 Kbar	Isothermal decompression	Satish-Kumar et al in prep

Mineral Abbreviations:　Amph-Amphibole, Ank-Ankerite, Bt-Biotite, Cc-Calcite, Chl-Chlorite, Clzo-Clinozoisite, Cpx-Clinopyroxene, Dol-Dolomite, Ep-Epidote, Fo-Forsterite, Grt-Garnet, Gr-Graphite, Kfld-Kfeldspar, Mus-Muscovite, Phl-Phlogopite, Plg-Plagioclase, Po-Pyrrhotite, Qtz-Quartz, Ru-Rutile, Scp-Scapolite, Sp-Spinel, Sph-Sphene, Wo-Wollastonite

Table 2. Calc-silicates of East Gondwana

Location	Continent	Mode of occurrence	Reference
Lutzow-Holm Bay	East Antarctica	Boudins and thin layers	Hiroi et al., (1987)
Prydz Bay	East Antarctica	Lenses and blocks	Motoyoshi et al., (1991)
Rauer Group	East Antarctica	Boudins	Harley and Buick, (1992)
Highland Compex	Sri Lanka	Interbedded with other metapelites	Hoeffbauer and Spiering, (1994)
Eastern Ghats	India	Bands and lenses	Dasgupta, (1993)
Kerala Khondalite Belt	India	Interbedded with other metapelites	Satish-Kumar et al. in prep

metamorphic conditions.

Scapolite in high-grade terrains is a potentially powerful mineral in constraining CO_2 activities during metamorphism. Recent studies on calcic-scapolite phase equilibria show that an increase in Al-Si disorder in scapolite structure is directly proportional to an increase in the P-T slope of the meonite-formation reaction. Also, the slope of meonite decarbonation equilibria changes from positive to negative in $T-X_{CO_2}$ space as a function of increasing Al-Si disorder (Moecher and Essene, 1990). Using this and the available thermodynamic data on calcic scapolite, the CO_2 activities of scapolite from different associations yielded interesting results on fluid activity in granulite geneses. Scapolites from granulite xenoliths and intrusives gave a CO_2 activity of <0.9, from high grade non-calcareous rocks gave a CO_2 activity of >0.7, and scapolites from calc-silicates yield a CO_2 activity of less than 0.5 (MOECHER and ESSENE, 1991). These results are consistent with the mineral equilibria of the phases in each of the rock types and are significant in discussing fluid processes in high grade terrains.

Thus recent studies have proved that wollastonite- and scapolite-bearing rocks are excellent monitors in constraining the fluid composition of regional metamorphic terrains. They also preserve mineral-reaction textures characteristic of post-peak metamorphic evolution. Hence the petrologic and metamorphic evolution of calc-silicates is a focus for intense debate on granulite petrogenesis.

The East Gondwana supercontinent is composed of a number of granulite-facies terrains from late Archaean to Proterozoic in age. Structural, petrological and geochronological studies on these granulites have been used to understand the tectonothermal history and continental juxtaposition of this supercontinent (YOSHIDA *et al.*, 1992; YOSHIDA and SANTOSH 1994; SHIRAISHI *et al.*, 1994). Calc-silicates have been reported from several crustal segments of East Gondwana (Table 1) and have been studied to understand the pressure-temperature-fluid histories of these granulite terrains

(Harley and Buick 1992, Hiroi et al., 1987; Harley and Santosh, 1995). Hence, a comparative study of calc-silicate reaction textures will help in a better understanding of the tectonothermal history of granulites in these continental masses. In this contribution the calc-silicates reactions and textures from East Antarctica, Sri Lanka and Peninsular India are discussed. A possible distinction based on reactions and textures on the pressure- temperature-fluid histories of the calc-silicates in East Gondwanan crustal fragments is also attempted.

2. Reactions and Textures in Calc-silicates
from East Gondwana

2.1. Calcite + Quartz = Wollastonite + CO$_2$ (Hiroi et al., 1987; Motoyoshi et al., 1991; Harley and Buick, 1992; Hoeffbauer and Spiering, 1994; this study)

This is one of the most important reactions in the granulite-facies calc-silicate assemblages. Wollastonite phase relations and its stability in different fluid compositons is vital in deducing the fluid conditions of the calc-silicates (Lamb and Valley, 1987). Wollastonite formation is favoured at higher temperatures and lower X_{CO_2} (Fig. 2A, B, C). This can be seen by the positive slope of the reaction curve in the T-X_{CO_2} space. At lower P-T-X_{CO_2} conditions the slope of the reaction curve is steep and hence, little increase in X_{CO_2} will make calcite-quartz assemblage stable. At higher pressures, the curve is shifted to higher temperatures and hence it is necessary that in high P-T granulites the calcite-quartz reaction occurs only in lower X_{CO_2} conditions than in low P-T granulites. Therefore it is clear that in order to stabilise wollastonite in high X_{CO_2} conditions, either very high temperature and high pressure or high temperature and lower pressure are required (Fig. 2A, C). As such conditions are not normally attained in the granulite P-T regime, wollastonite is considered to have been
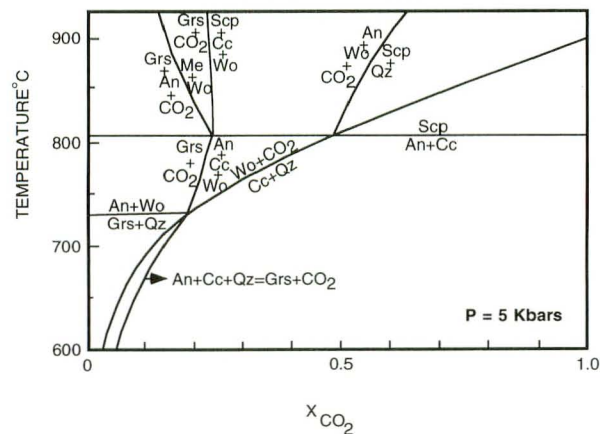

Fig. 2 **(A)**. T-X_{CO_2} diagram showing the relevant reaction curves (see text for details) in the system CaO-Al$_2$O$_3$-SiO$_2$-CO$_2$-H$_2$O at 5 kbar (modified after Moecher and Essene 1990).
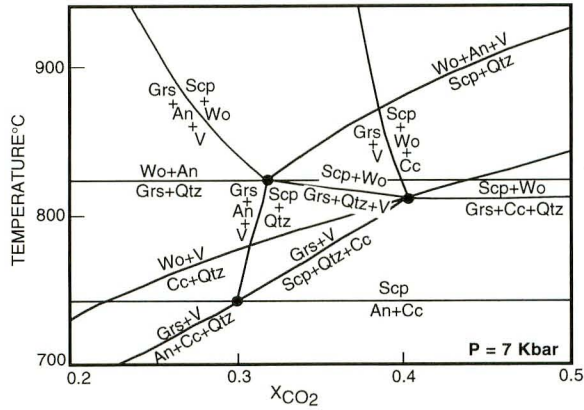
Fig. 2 (**B**). T-X_{CO_2} diagram showing the relevant reaction curves (see text for details) in the system $CaO-Al_2O_3-SiO_2-CO_2-H_2O$ at 7 kbar (modified after Harley et al. 1994).
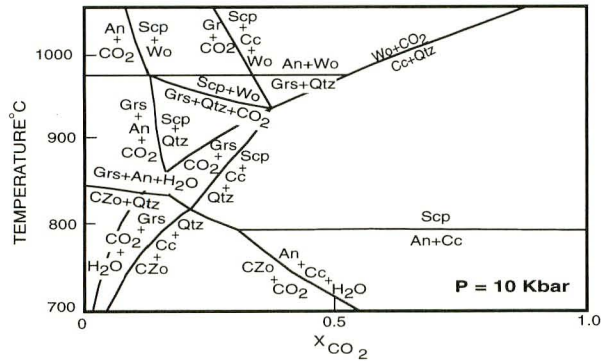

Fig. 2 (**C**). T-X_{CO_2} diagram showing the relevant reaction curves (see text for details) in the system $CaO-Al_2O_3-SiO_2-CO_2-H_2O$ at 10 kbar (modified after Moecher and Essene 1990)
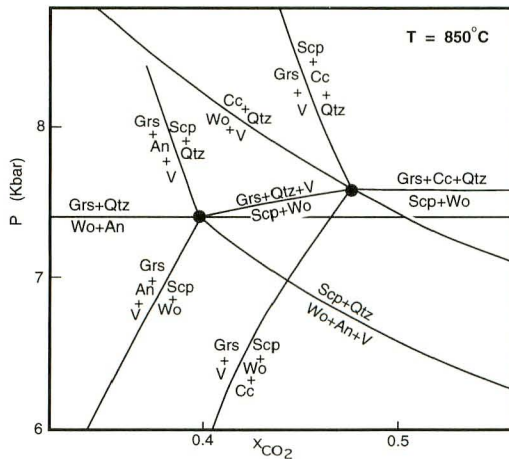

Fig. 3. P-X_{CO_2} diagram of the common reactions reported from East Gondwana high temperature calc-silicates (modified after HARLEY *et al.* 1994).

stabilized under H_2O-rich or vapor-free environments.

Wollastonite has been reported from calc-silicates of East Gondwana. To stabilise wollastonite in the assemblage at the P-T regimes of these granulite terrains, the X_{CO_2} of the system should be around 0.2. But in many of these terrains, the associated rocks have stabilised in higher X_{CO_2} conditions. This is indicative of an internally controlled fluid composition. In the southwestern part of the Highland Complex, Sri Lanka, and in the Kerala Khondalite Belt, South India, wollastonite characteristically shows grain-boundary retrogression (Fig. 4A and 4B). In Lützow Holm Bay, wollastonite has been reported from Soya Coast, which has the highest grade of metamorphism in the region and occurs in association with quartz and calcite (Hiroi et al., 1987). These textural relations show that there was a carbonic fluid infiltration in the terrain during earlier stages in the cooling history, instrumental in the charnockite formation, and also partial retrogression of wollastonite in the calc-silicates. Contrary to this, in the Eastern Ghats, India and Prydz Bay and Rauer Group, East Antarctica, wollastonite does not show any retrogression but shows other reactions which are discussed below. In these two terrains wollastonite occurs both as a primary phase as well as a secondary phase. The primary phase is thought to be the result of the reaction under discussion during the prograde path of metamorphism (Harley and Buick, 1992; Motoyoshi et al., 1991). In Bolingen island, East Antarctica, the occurrence of wollastonite in the calc-silicates indicates a low X_{CO_2} and a heterogeneous fluid flow with the adjacent gneisses (Motoyoshi et al., 1991).

2.2. Calcite + 3 plagioclase = Scapolite (Hiroi et al., 1987; Motoyoshi et al., 1991; Harley and Buick, 1992; Hoefbauer and Spiering, 1994; this study)

Scapolite is a solid-solution series from the sodic end member, marialite, to the calcic end member, meionite. Its volatile content can be either CO_3, Cl or SO_3. Recent advances in scapolite phase equilibria have shown that the activity of CO_2 controls the scapolite stability and can be used as an indicator of carbonic fluids in the deep crust (Moecher and Essene, 1991). This reaction is almost independent of pressure and fluid conditions and is temperature controlled (Figs. 2A, B, C and 3) and hence it can be used as a potential thermometer (Goldsmith and Newton, 1977; Ellis, 1978; Oterdom and Wenk, 1983). Scapolites from calc-silicates in different terrains have yielded low CO_2 activities, which is also supported by the presence of wollastonite in these calc-silicates (Moecher and Essene, 1990).

Scapolite is ubiquitously present in all the calc-silicates studied from East Gondwana and has an important bearing on reactions in these rocks. The Eq An ($= 100$ (Al-3)/3) values of scapolites from calc-silicates of East Gondwana range from 70 to 85. Using the meionite thermometer, Motoyoshi et al. (1991) deduced a maximum temperature of 760°C at 6 kbars for the Prydz Bay calc-silicates. In the Highland Complex of Sri Lanka, scapolite is not in equilibrium with plagioclase and calcite, indicating that either one of the reactants might have been consumed completely. The absence of scapolite

taking part in other reactions such as, grossular formation, have been interpreted to be due to low X_{CO_2} condition at peak metamorphic temperature (HOEFBAUER and SPIERING, 1994). In the marble assemblages of the Kerala Khondalite Belt, South India, calcite and plagioclase typically show a grain-boundary reaction to form scapolite (Fig. A, B). This indicates that the peak metamorphism has just reached the reaction curve of scapolite formation. In the quartz-free assemblages of the Rauer group calc-silicates, the most meionitic scapolites are replaced by anorthite-calcite symplectites. This restriction of high meionitic scapolites has been used to constrain the temperature of this reaction to be around 850°C (HARLEY and BUICK, 1992)

2.3. Scapolite = 3 plagioclase + Calcite + Quartz (HOEFBAUER and SPIERING, 1994; MOTOYOSHI *et al.*, 1991; this study)

This reaction is normally a retrograde reaction in calc-silicates. It is accompanied by the presence of small quantities of quartz, which is different from the prograde reaction discussed above (reaction-2.2), and may either be due to a small excess of SiO_2 in scapolite over the ideal composition (EVANS *et al.*, 1969) or to SiO_2 being released together with Na_2O from scapolite, due to the more sodic nature of scapolite than the associated plagioclase (GOLDSMITH and NEWTON, 1977; HARLEY, 1987). Scapolite retrogression in calc-silicates has been reported from Sri Lanka and East Antarctica as well as in the Kerala Khondalite Belt, South India. Most of the scapolites in the Highland Complex, Sri Lanka, show this reaction and has been interpreted as occurring at about 600–700°C. In Prydz Bay, this reaction has also been noticed. This retrograde reaction has been widely noticed in calc-silicates of the Kerala Khondalite Belt, South India (Fig. 6A, B). In Eastern Ghats, India, or the Rauer group, East Antarctica, this reaction texture is not by far documented.

2.4. 2Wollastonite + Plagioclase = Grossular + Quartz (MOTOYOSHI *et al.*, 1991; HIROI *et al.*, 1987; HARLEY and BUICK, 1992; this study)

This reaction is independent of a fluid phase, but is controlled by wollastonite stability and hence, the conditions described in reaction (1) will be applicable to this also (Fig. 2A, B, C and 3). Within the wollastonite stability field this reaction is not controlled by CO_2 variations, as can be seen from the horizontal curve in the T-X_{CO_2} space, and hence is temperature-dependant (eg. Fig. 2A). The reaction proceeds with increasing temperature and pressure until one of the reactants is exhausted, with higher pressure favouring grossular in the assemblage and higher temperature favouring the wollastonite and plagioclase assemblage (HUCKENHOLZ *et al.*, 1977, 1981). The presence of Na_2O in plagioclase and Fe_2O_3 in grossular have opposite effects on P-T conditions of this reaction (WINDER and BOETCHER, 1976). Accordingly, an additional 6 mole percent of albite shifts the curve of this reaction to the low temperature side within 10°C,

whereas the univariant curve shifts to about 10°C on the high temperature side, with 20 mole percent of the andradite component in grossular. When the garnet becomes a solid solution, the Fe-Mg components in the garnet are resorbed to form clinopyroxene in the product side. With the decreasing grossular content in the garnet the clinopyroxene abundance increases in the intergrowth (HARLEY and BUICK, 1992).

Lützow Holm Bay data show that both grossular and anorthite are close to end members and that the P-T conditions of the observed reaction can be compared with the univarient end member reaction curve (HIROL *et al.*, 1987). This reaction has been cited as one of the most important reactions from Lutzow Holm Bay in deducing the P-T condition of calc-silicates. It has not yet been reported from Sri Lanka and South India and even grossular is comparatively rare in these terrains. The occurrence of garnet in one of the locations in the Kerala Khondalite Belt may have resulted from this reaction as there is primary plagioclase in the assemblage. The pressure-temperature conditions of the terrain also limit the formation of garnet through this reaction or the reaction between anorthite, calcite and quartz, which is discussed in detail below. In the quartz-bearing layers that lack initial plagioclase, wollastonite - plagioclase symplectites have been reported from the Rauer group in East Antarctica. Additional clinopyroxene occurs in places as a product phase, indicating the involvement of a garnet solid solution instead of a pure grossular (HARLEY and BUICK, 1992). In Prydz Bay, East Antarctica, grossular coronas are observed in wollastonite-plagioclase contacts, indicating this reaction (MOTOYOSHI *et al.*, 1991).

2.5. Wollastonite + Anorthite + CO_2 = Scapolite + Quartz. (HARLEY and SANTOSH, 1994 ; HARLEY and BUICK, 1992).

This reaction characteristically occurs in CO_2-rich conditions. The reaction has a steep slope in T-X_{CO_2} space, with a higher X_{CO_2} favouring scapolite + quartz assemblage. At 5 Kbar, the reaction progresses only if the fluid compostion is about 0.5 X_{CO_2}, with a higher temperature and lower X_{CO_2} favouring the anorthite-wollastonite assemblage and lower temperature and higher X_{CO_2} favouring the scapolite-quartz assemblage (Fig. 2A). This reaction is also characteristic of protoliths having less calcite, as calcite can react with anorthite to form scapolite in the same P-T-X_{CO_2} conditions of this reaction. Theoretical constraints show that scapolite and quartz react forming wollastonite and anorthite in the volume proportion of 11.7 : 88.3 (HARLEY and BUICK, 1992). The reaction forming wollastonite and anorthite from scapolite and quartz has been reported from the Rauer group, East Antarctica. Wollastonite and anorthite coronas forming between scapolite and quartz have been noticed in garnet absent assemblages (HARLEY and BUICK, 1992). In Nuliyam, South India, HARLEY and SANTOSH (1994) have described this reaction resulting in scapolite-quartz symplectites, which also implies a post peak metamorphic CO_2 infiltration.
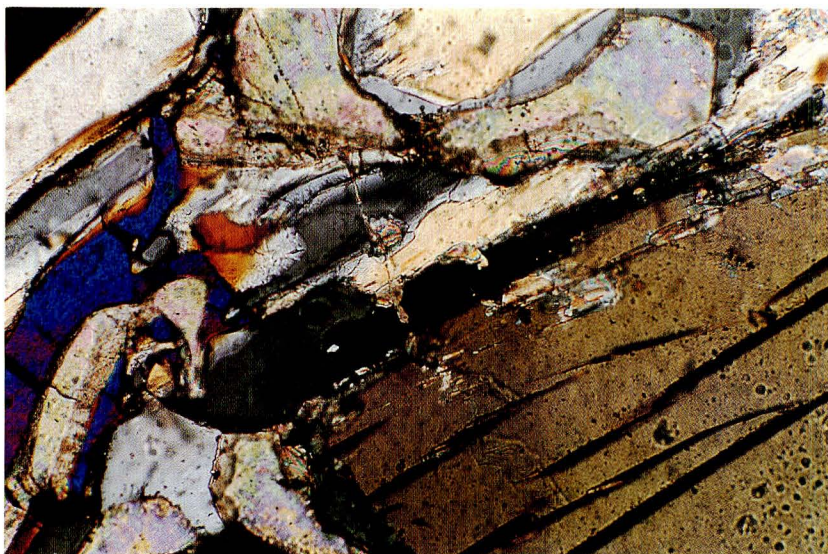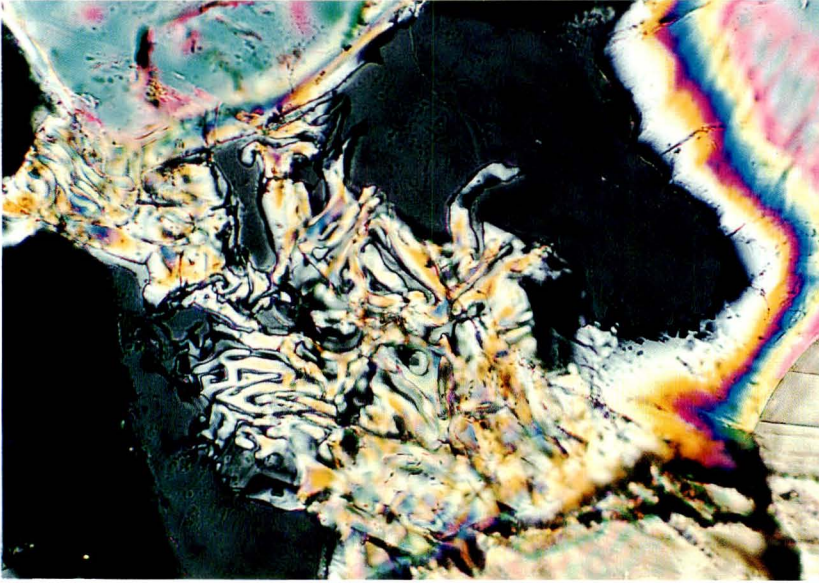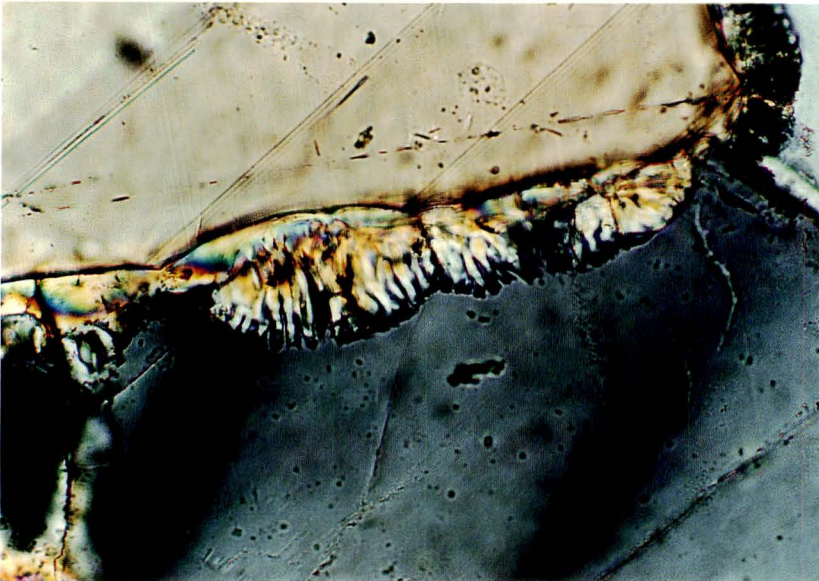
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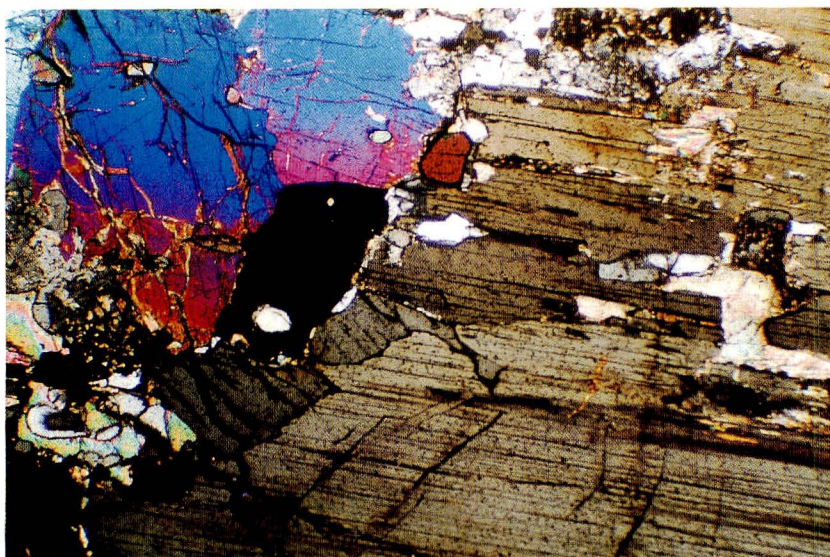
B

Fig. 4. (**A** and **B**) Wollastonite partial retrograde reaction resulting in fine grained calcite quartz rims. Also notice the stable coexistence of scapolite with wollastonite. Length of the photomicrograph is 2 mm.
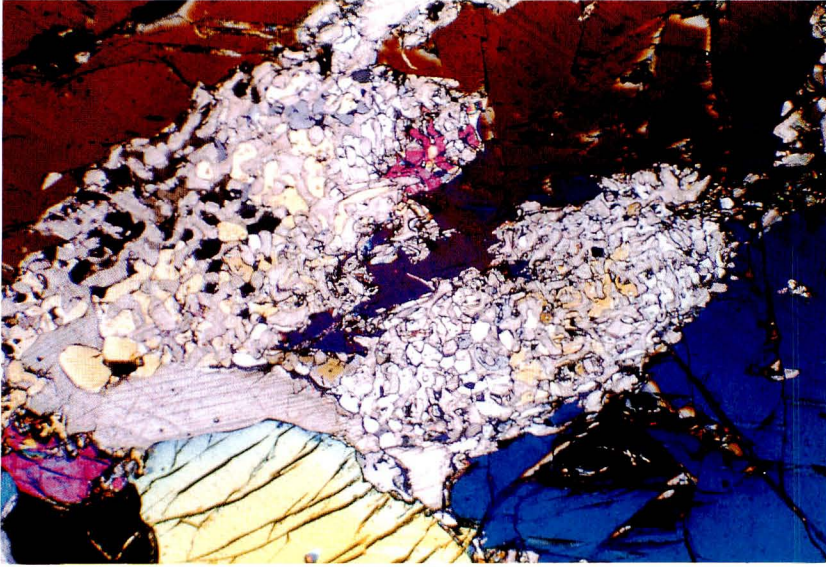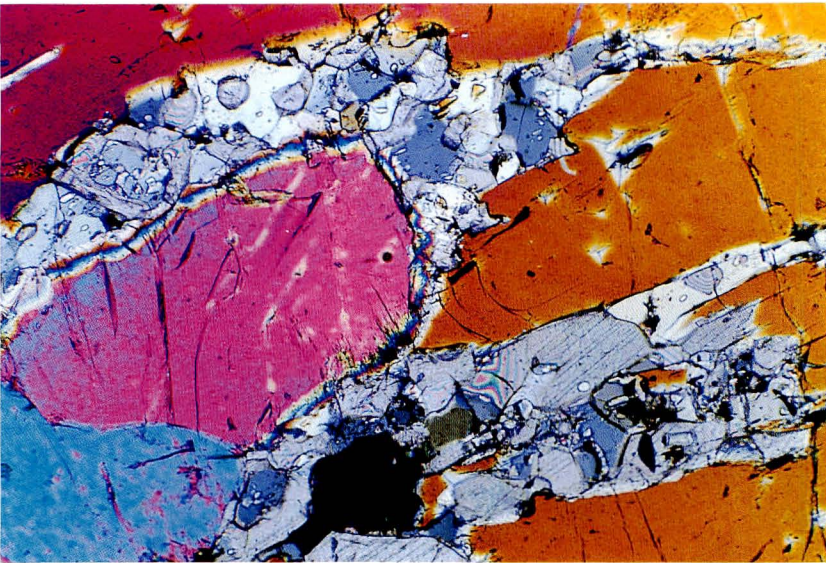
A

B

Fig. 5. (**A** and **B**)   Grain boundary reaction between calcite and plagioclase resulting in the formation of scapolite. Length of the photomicrograph is 2 mm.
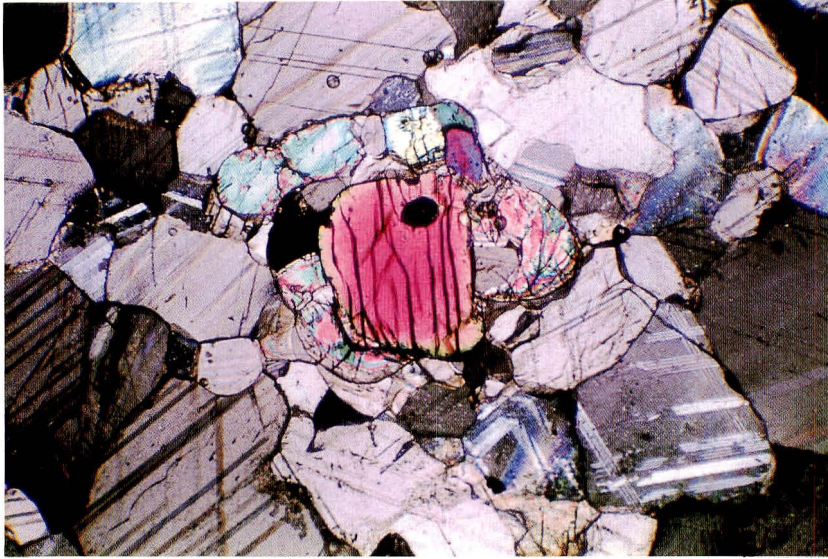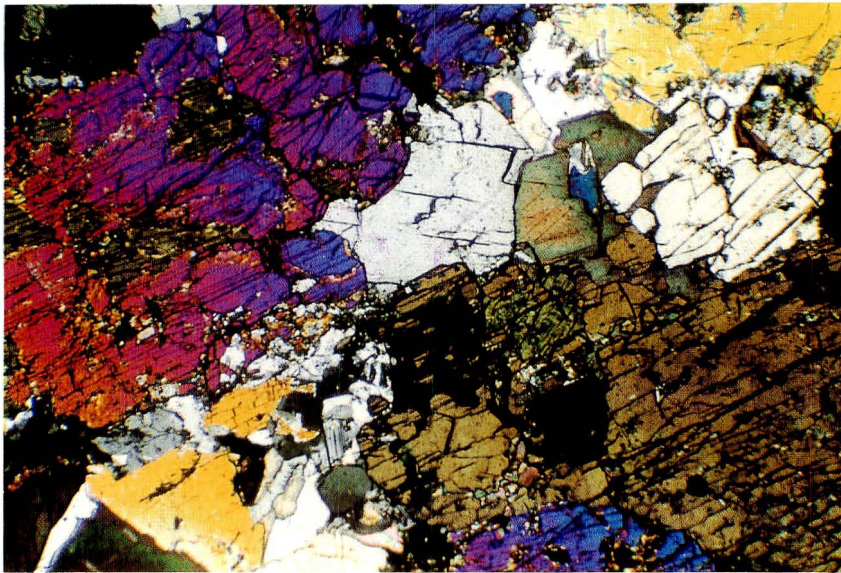
A

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Fig. 6. (**A** and **B**)   Scapolite retrogressing to fine-grained assemblage of calcite plagioclase and minor amounts of quartz.   Length of the photomicrograph is 4 mm.

A

Fig. 7. **(A)**. Forsterite and calcite reacting in the presence of CO_2 to form a rim of dolomite and diopside. Length of the photomicrograph is 8 mm.

B

Fig. 7. **(B)** Retrogression of clinopyroxene to amphibole imparted by a late-stage hydrothermal fluid infiltration. Length of the photomicrograph is 4 mm.

2.6 3Wollastonite + Scapolite + 2Calcite = 3Grossular + 3CO$_2$ (Harley and Buick, 1992; Motoyoshi *et al.*, 1991; Dasgupta, 1993).

Formation of grossular from this reaction occurs only in high temperatures and medium to high pressures ($\sim >820$ at 5kbars, Fig. 2B). This reaction is much affected by a small variation in the fluid composition, which is clearly shown by the steep slope of the reaction curve in the T- X_{CO_2} diagram (Fig. 2A, B, C). A wollastonite-scapolite assemblage is favoured by a CO$_2$ rich fluid condition, whereas grossular is favoured in a low-CO$_2$ fluid condition. The dependence of pressure and fluid composition is that at a decreased pressure condition, the reaction progresses with a low CO$_2$ activity and vice versa (Fig. 2C). Hence, this reaction is important in high-temperature granulites, which can be useful in deducing the post-peak metamorphic trajectory of the terrain. This reaction has been documented from the Eastern Ghats, where porphyroblastic garnets occur in granoblastic association with calcite, wollastonite and scapolite (Dasgupta, 1993). This reaction is typical of quartz-deficient layers in which a garnet rim separates scapolite and calcite (Harley *et al.*, 1994).

2.7. 5Wollastonite + Scapolite = 3Grossular + 2Quartz + CO$_2$ (Haroey and Buick, 1992; Dasgupta, 1993).

Wollastonite and scapolite react to form grossular and quartz only at high temperatures and pressures at an average X_{CO_2} of 0.3-0.4 (Fig. 2B, C). A slight variation in pressure, temperature or CO$_2$ activity shifts the reaction to make either the reactant-side or the product-side mineral assemblages stable. Lower pressure and high temperature favour the wollastonite and scapolite assemblage, whereas the reverse conditions favour the grossular and quartz assemblage (Fig. 2B, C). The reaction is metastable at pressures lower than 7 kbar, because the three invariant points (Fig. 3) contract as the thermal stability of wollastonite + scapolite approaches that of scapolite (Ellis, 1978, Warren *et al.*, 1987). This reaction is characteristic of isobarically cooled terrains, as is evident from figures 2A, B and C. This is a high-temperature decarbonation reaction which can produce CO$_2$ during retrogression. This CO$_2$ can be trapped as post metamorphic fluid inclusions in granulites (Harley *et al.*, 1994). In the Eastern Ghats, this reaction has been documented and is interpreted to be the result of isobaric cooling (Dasgupta, 1993). In quartz-present locations, the reverse reaction has been reported in the Rauer group, where porphyroblastic garnets are replaced by wollastonite and scapolite symplectites, which is considered to represent a high P-T, clockwise prograde path (Harley and Buick, 1992).

2.8. CaTs + Wollastonite = Grossular (Dasgupta, 1993)

Narrow alumina-depleted rims in clinopyroxene, which coexists with other mineral phases, have been attributed to the resorption of Ca-Tschermak's component. This depletion is normally noticed with this reaction, which results in garnet rims separating

clinopyroxene and wollastonite.   The reaction proceeds to the right side with decreasing temperature or increasing pressure.   WARREN *et al.* (1987) suggested that this alumina depletion is due to the influx of hydrous fluids during the retrograde metamorphic path.   In the Eastern Ghats, this reaction has been interpreted as resulting in coronal garnet between clinopyroxene and scapolite, where the clinopyroxene is depleted in alumina (DASGUPTA, 1993).

2.9.   Wollastonite + Hedenbergite + O_2 = Andradite + Quartz. (DASGUPTA, 1993)

The presence of andradite garnet has been attributed to the local increase of f_{O_2} and results in the reaction of wollastonite and hedenbergite.   This is also a high-temperature pressure reaction.   Occasional occurrence of andradite garnet in the Eastern Ghats and in the Rauer group has been interpreted to be the result of this reaction (DASGUPTA, 1993; HARLEY and BUICK, 1992).

2.10.   Anorthite + 2 Calcite + Quartz = Grossular + $2CO_2$ (HIROI *et al.*, 1987)

This reaction proceeds to higher temperatures as the CO_2 increases, until it reaches the wollastonite-formation reaction curve, after which calcite and quartz react to form wollastonite (e.g., 730°C at 5 kbar).   A higher temperature and lower X_{CO_2} favour grossular in the assemblage at 5 kbar, where as a lower temperature at higher X_{CO_2} favours anorthite, calcite and quartz in the assemblage (Fig. 2A).   At lower pressures, the temperature of the invariant point with anorthite + calcite reacting to form zoisite is still further lowered, and hence, grossular can form at even lower temperature provided the X_{CO_2} is still lower (MOECHER and ESSENE, 1990).   At high pressure, the invariant point crosses the wollastonite-forming reaction and hence this reaction will not occur (HARLEY and BUICK, 1992; MOECHER and ESSENE, 1990).   Compared to the reaction of wollastonite with anorthite, forming grossular, this reaction can take place in a range of temperatures but still X_{CO_2} variation of this reaction is only less than 0.3 at 5 kbar.   The occurrence of plagioclase, calcite and quartz inclusions in garnet porphyroblasts indicates this reaction in Lutzow Holm Bay (HIROI *et al.*, 1987).   In assemblages that lack wollastonite in the Rauer group, East Antarctica, fine garnet rims occur between calcite and plagioclase implying this reaction (HARLEY and BUICK, 1992).

2.11.   Anorthite + Wollastonite + Calcite = Grossular + CO_2 (HIROI *et al.*, 1987)

This reaction is actually a continuation of the above mentioned reaction (reaction-2.10).   It favours constant X_{CO_2} conditions of about 0.20 at 5 kbar (Fig. 2A) and proceeds until the temperature at which anorthite and calcite can react to form scapolite, as has been discussed earlier (reaction-2.2).   A lower X_{CO_2} at any temperature during this reaction favours grossular in the assemblage, whereas a higher X_{CO_2} favours wollastonite, anorthite and calcite (Fig. 2A, B, C).   At higher pressures, anorthite and calcite react to form scapolite and hence this reaction is metastable, and scapolite and wollastonite react under favorable fluid conditions to form grossular, which was discussed

earlier (reaction-2.6). Thin garnet films between wollastonite and plagioclase in Lützow Holm Bay calc-silicates have been attributed to result from this reaction (HIROI *et al.*, 1987).

2.12. Grossular + CO_2 + H_2O = Epidote + Calcite + Quartz
(HIROI *et al.*, 1987; MOTOYOSHI *et al.*, 1991)

Epidote is found only rarely in granulite facies conditions and if found, is interpreted to be a late retrogression product of garnet. This reaction normally occurs due to the infiltration of hydrous fluids. Epidote has been reported in Prince Olav coast in Lutzow Holm Bay and also from Prydz Bay, East Antarctica.

2.13. Clinopyroxene + H_2O + CO_2 = Tremolite + Calcite + Quartz (MOTOYOSHI *et al.*, 1991; this study).

Cooling and rehydration processes are documented by decomposition textures of clinopyroxene in calc-silicates. Clinopyroxene porphyroblasts can be seen in places surrounded by fine-grained assemblage of tremolitic amphibole, calcite and quartz, indicating this reaction. Clinopyroxene is retrogressed to form amphibole in calc-silicates which are affected by a late-stage hydrous fluid infiltration. It has been noticed in calc-silicates from Prydz Bay and the Kerala Khondalite Belt (Fig. 7A).

Now we will discuss some of the important reactions which are of particular interest in marbles from the Kerala Khondalite Belt in South India, the Highland Complex of Sri Lanka and Lutzow Holm Bay in East Antarctica.

2.14. 3Dolomite + K-feldspar + H_2O = Phlogopite + 3Calcite + $3CO_2$
(HOEFFBAUER and SPIERING, 1994; this study)

If K-feldspar is present in the protolith, it reacts with dolomite to form phlogopite in the resulting paragenesis. This reaction proceeds to the right with increasing temperatures in the T-X_{CO_2} space, with a higher X_{CO_2} favouring a low temperature for the reaction (Fig. 8A, B). This can be the reason for the presence of phlogopite in most of the impure marbles, as a lower temperature favours a hydrous fluid in the system. With increasing pressure the reaction is shifted to higher temperatures, favouring the stability of phlogopite. During the prograde sectors of metamorphism the reaction proceeds fast, as the increase in temperature also buffers the CO_2 activity of the system, until one of the reactants is completely exhausted. Phlogopite coexisting with calcite in the marble assemblages in the Kerala Khondalite Belt indicates this reaction. The stability of phlogopite in the assemblage indicates an X_{CO_2} of less than 0.95 at 700°C and 5 kbar. In the Highland Complex of Sri Lanka the reaction is documented by the presence of K-feldspar in the protolith (Hoeffbauer and Spiering, 1994).
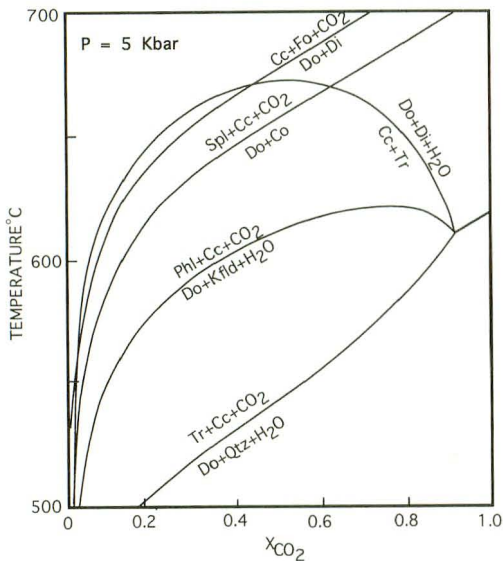
Fig. 8. (A). T-X_{CO_2} section, showing the important reactions in marble assemblages of East Gondwana, in the system K_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O-CO_2 at 5 kbar (modified after Hoeffbauer and Spiering, 1994).
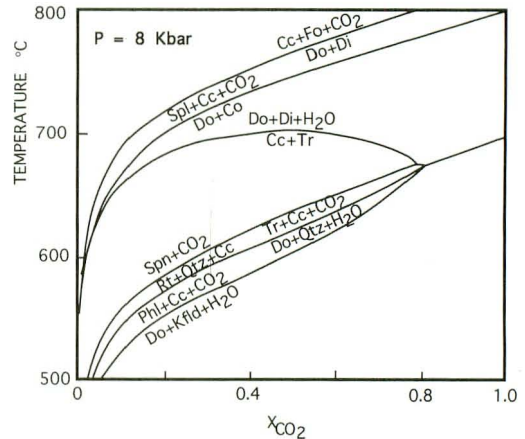
Fig. 8. (B). T-X_{CO_2} section, showing the important reactions in marble assemblages of the East Gondwana, in the system K_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O-CO_2 at 8 kbar (modified after Hoeffbauer and Spiering, 1994).

2.15.   5Dolomite + 8Quartz + H2O = Tremolite + 3Calcite + 7CO₂ (HOEFFBAUER and SPIERING, 1994)

This reaction is controlled by all the three parameters, namely temperature, pressure and fluid composition. At 5 kbar, a lower X_{CO_2} in the system needs only lower temperature to form tremolite; an increase in X_{CO_2} increases the temperature of tremolite formation. At about 600°C and 0.8 X_{CO_2} the curve reaches the invariant point B (Fig. 8A, B) whereby the reaction between dolomite and quartz to form diopside proceeds. At higher pressures, the optimum X_{CO_2} at any temperature of the reaction is less than that at lower pressures, but it is clear that at any pressure, the reaction progresses with a high temperature only if the CO_2 activity is higher. This reaction proceeds with the consumption of the hydrous fluid phase and with an increment of CO_2. With increasing temperature, this reaction proceeds until one of the reactants is exhausted or the invariant point is reached (Fig. 8A). The tremolite thus formed during this reaction can further react with calcite to form dolomite and diopside, or if quartz is also present it produces diopside alone with increasing temperature.

Tremolite is ubiquitously present in marble assemblages from the Kerala Khondalite Belt-south India, the Highland Complex,Sri Lanka and Lutzow Holm Bay,East Antarctica. The coexistence of tremolite and calcite and the absence of dolomite and quartz is indicative of this reaction in these terrains (HOEFBAUER and SPIERING, 1994; HIROI and KOJIMA, 1988).

2.16.   Dolomite $+$ 2Quartz $=$ Diopside $+$ 2CO$_2$

This is a typical reaction occuring in high X_{CO_2} conditions in a wide range of granulite P-T conditions. The reaction proceeds at 5 kbar only if the temperature is more than 620°C and at X_{CO_2} more than 0.83 (Fig. 8A, B) When the pressure is increased the curve is shifted to higher temperatures while the X_{CO_2} in the system remains unaffected. At lower X_{CO_2} compositions in the fluid phase, dolomite and quartz react to form tremolite and calcite in the paragenesis (reaction-2.14). In marble assemblages it is difficult to achieve CO$_2$-rich fluid composition unless CO$_2$ has been enhanced by the other decarbonation reactions. Another constraint is that the protoliths should be rich in dolomite and quartz rather than in calcite or other phases.

This reaction is common not only in the marble assemblages but also in calc-silicates. In the calc-silicates and marble assemblages of the Kerala Khondalite Belt, the occurrence of diopside can be attributed to this reaction. In some locations near the Achankovil Shear Zone, southern India, assemblages consisting of only diopside + quartz indicate that the dolomite in the protolith was exhausted during the progress of this reaction. The marbles assemblages in the Highland Complex and in Lutzow Holm Bay also have diopside in the paragenesis indicating this reaction (HOEFFBAUER and SPIERING, 1994; HIROI and KOJIMA, 1988)

2.17.   3Calcite $+$ Tremolite $=$ Dolomite $+$ 4Diopside $+$ H$_2$O $+$ CO$_2$. (HOEFFBAUER and SPIERING, 1994; HIROI and KOJIMA, 1988)

Calcite and tremolite react at lower X_{CO_2} with a positive slope in the T-X_{CO_2} space to form dolomite and diopside, whereas at higher X_{CO_2} the reaction has a negative slope (Fig. 8A, B). This indicates that at medium X_{CO_2} conditions the reaction needs maximum temperatures, and that a lower or higher X_{CO_2} requires only lesser temperature to stabilise dolomite and diopside. At higher pressure, the reaction does not change much, except that in higher X_{CO_2}, the slope of the reaction is very shallow, indicating that the reaction proceeds without much change in temperature. This reaction buffers both H$_2$O and CO$_2$ in the system The ratio of molar volume of calcite and tremolite and the X_{CO_2} control the products of this reaction. If more tremolite is present in the paragenesis it favours forsterite and diopside in the product side. If the system has a lower X_{CO_2} the reaction resulting in diopside and forsterite is favoured. The dolomite and diopside thus formed can react to form forsterite if the temperature is further increased (reaction-2.18). The coexistence of dolomite and diopside in the Highland Complex, Sri Lanka, can be cited as an example for this reaction (HOEFFBAUER and SPIERING, 1994)

2.18.   Dolomite $+$ Corundum $=$ Spinel $+$ Calcite $+$ CO$_2$ (HOEFFBAUER and SPIERING, 1994 ; HIROI and KOJIMA, 1988; this study)

If corundum is present in the initial assemblage it will react with dolomite to form

spinel. This reaction proceeds at lower temperatures if there is little X_{CO_2} in the system. At lower temperatures a slight variation in the X_{CO_2} will decide the mineral to be stable in the parageneses. A change in pressure in the system has great effect in this reaction. For example, at 5 kbar, spinel can form at 700°C if the X_{CO_2} is greater than 0.9, whereas at 8 kbars spinel can form at 700°C only if the X_{CO_2} is 0.2. This is clearly evident in the shift of the slope in the reaction curves at different pressures in the T-X_{CO_2} space (Fig. 8A, B).

Spinel is present in the marble paragenesis of the Kerala Khondalite Belt, South India, the Highland Complex, Sri Lanka, and Lutzow Holm Bay, East Antarctica (HOEFFBAUER and SPIERING, 1994 ; HIROI and KOJIMA, 1988 ; this study). Coexisting spinel and calcite in the absence of corrundum in the assemblage suggest this reaction during prograde metamorphism.

2.19.   3Dolomite + Diopside = 4Calcite + 2Forsterite + CO$_2$
(HOEFFBAUER and SPIERING, 1994; this study)

This is a common reaction in impure marbles which have undergone high grade metamorphism. At 5 kbars the reaction proceeds only above 670°C at an X_{CO_2} of 0.5, but above this temperature an increase in CO_2 content does not affect much the temperature of formation of forsterite, as can be seen by the near horizontality of the reaction curve in the T-X_{CO_2} diagram (Fig. 8A, B). A slight increase in temperature favours forsterite in the assemblage, a decrease in temperature favouring diopside in the assemblage. At lower temperatures, forsterite is formed by the reaction of tremolite with calcite or dolomite (cf. reactions-2.12 and 2.14). These two reactions have steep slopes in T-X_{CO_2} space, and hence it is clear that a slight increment in X_{CO_2} imparts a large increase in temperature for forsterite to stabilize. At higher pressure conditions as tremolite is not stable, these two reactions are not valid. Hence the reaction between diopside and dolomite can occur in a complete set of X_{CO_2} conditions; an increase in X_{CO_2} increases the temperature of formation of forsterite. Another interesting thing to notice in this reaction is that the formation of forsterite buffers the CO_2 activity in the rock. This reaction is one of the prominent reactions recorded in the northern part of the Highland Complex of Sri Lanka. Characteristic fine-grained assemblages of dolomite and diopside surrounding forsterite grains can be observed in the marble assemblages of the Kerala Khondalite Belt (Fig. 7B), which implies that the retrograde reaction occurred in this terrain.

2.20.   Rutile + Quartz + Calcite = Sphene + CO$_2$ (HOEFFBAUER and SPIERING, 1994; this study)

This reaction is identical to reaction 14 in phase relations. The reaction proceeds at lower pressure with a steeper slope. A little change in the fluid condition towards a higher CO_2 content should accompany a big difference in temperature, in order to stabilize sphene in the assemblage (Fig. 8A). But at higher pressures, the reaction is

not much affected by the variation in X_{CO_2} content of the system, as is clear from the T-X_{CO_2} curve for the reaction (Fig. 8B). The reaction proceeds until one of the reactants is exhausted, most commonly rutile, as it is only an accessory phase in the system. Sphene has been reported from almost all of the calc-silicates in the granulite terrains and also from marbles which have been metamorphosed to granulite facies conditions, and is the result of this reaction. Rutile is a common accessory phase in impure carbonates and hence, sphene is often present in metacarbonates.

3. Discussion

Granulite facies calc-silicates provide vital clues on fluid regimes in the lower crust. The reactions involving calc-silicate minerals are sensitive to even minor changes in fluid composition at any given pressure-temperature conditions. This is evident from the reactions described in this paper. In some granulite facies terrains the orthopyroxene-bearing lithologies are believed to be stabilised under CO_2 rich fluid conditions. One of the mechanisms attributed for the CO_2 enhancement is a pervasive influx of CO_2 from deeper levels of Earth's crust or upper mantle (NEWTON *et al.*, 1980). But in terrains which have undergone such a pervasive influx of carbonic fluid, only a few mineral species in the calc-silicates can be stable in normal granulite pressure temperature conditions. Recent studies have considered that most of the calc-silicate mineral assemblages in granulite terrains imply an internally controlled fluid regime during the peak metamorphism.

The common mineral assemblage in the calc-silicates in granulite terrains is wollastonite + scapolite + garnet + plagioclase + clinopyroxene with quartz + calcite + K-feldspar + sphene and graphite occurring as minor phases (HARLEY *et al.*, 1994). Of these minerals, garnet, clinopyroxene, scapolite and plagioclase are solid solutions. Hence the reactions involving these minerals should be considered with the variations in their chemical compositions.

The reactions in the granulite facies calc-silicates can be used for the interpretation of the post-peak metamorphic history. The reactions involving wollastonite and scapolite (reactions 2.5 and 2.6) are typical in this respect. An isothermal decompression is characteristic of the formation of wollastonite from grossular, whereas grossular rims on wollastonite and scapolite are indicative of isobaric cooling. Another typical reaction which can distinguish post-metamorphic evolution is the reaction between grossular + quartz and anorthite + wollastonite (reaction 2.4). In terrains which have undergone decompressional histories, wollastonite-anorthite intergrowth is seen in between garnet and quartz, whereas in isobarically cooled terrains garnet-quartz coronas form between wollastonite and anorthite. To stabilise grossular bearing assemblages in granulite-facies terrains, the CO_2-fluid-rock ratios should be low (0.1- HARLEY and BUICK, 1992). Several recent reports of grossular bearing calc-silicates from different granulite terrains imply that most of these terrains have not witnessed pervasive influx of carbonic fluids in the peak metamorphic conditions.

The retrograde reactions in calc-silicates are of considerable interest in deciphering changing fluid regimes. At least two episodes of fluid influx can be deduced from the post-peak metamorphic reaction textures preserved in East Gondwana calc-silicates. At peak metamorphism, the mineral assemblages indicate an internally controlled fluid regime. This is evidenced by the equilibrium assemblage of wollastonite-scapolite and grossular in the calc-silicates as well as the orthopyroxene bearing anhydrous assemblages in adjacent lithologies. During the decompressional path, there is evidence for structurally controlled carbonic fluid infiltration in some terrains. The formation of incipient charnockites (Yoshida and Santosh, 1994) and partial retrogression of the wollastonites in the calc-silicates can be correlated to this. The evidence for a late-stage, hydrous fluid infiltration comes from the replacement of clinopyroxenes to form amphiboles and also plagioclase to form epidote and garnet. These textures are common in the calc-silicates of East Gondwana.

The reactions which we have discussed are representative of regionally metamorphosed calc-silicates. The reactions involving wollastonite and scapolite are of much interest in the light of their close relation with varying X_{CO_2} in the system. At higher temperatures and pressures the reactions can be clearly seen to be controlled by the CO_2 content of the system, as most of the reactions have steep slopes in T-X_{CO_2} and P-X_{CO_2} space (Fig. 2A, B, C and 3). Grossular-forming reactions in calc-silicates can mostly be explained either by isobaric cooling (Fig. 1) or during prograde sectors of clockwise P-T paths. Warren et al. (1987) suggested, based on grossular rims on scapolite with wollastonite, that cooling was accompanied by an influx of hydrous fluids. But recent models indicate that if pressure is higher than 6 kbars, grossular rims can form if the terrain is isobarically cooled below 850°C (Harley and Buick, 1992). In the Rauer Group, East Antarctica grossular garnet breaks down to form wollastonite, scapolite, plagioclase, calcite and quartz through the reactions 2.4, 2.5, 2.6, 2.7, 2.9 and 2.10 (Harley and Buick, 1992; Harley et al., 1994). These reactions are clearly indicative of an isothermal decompression with little or no external CO_2 influx. In the Eastern Ghats, India, the mineral assemblages in calc-silicates are indicative of extremely high P-T conditions of about 9 ± 1 kbar and 950°C (Dasgupta, 1993). The contrasting mineral assemblages are attributed to the difference in X_{CO_2}, f_{O_2}, and f_{HCl} in the fluid composi-tion, and to the Na content in the bulk composition (Dasgupta, 1993).

The calc-silicates from Lutzow Holm Bay of East Antarctica, the Highland Complex of Sri Lanka and the Kerala Khondalite Belt of South India have many similarities. The metamorphic conditions in these terrains are similar and the P-T evolutions of these terrains are all correlated to isothermal decompression. The mineral assemblages and reaction textures are typically of medium P-T granulites and hence can be attributed to lesser involvement of garnet in the reactions. Wherever garnet has been reported, it has most possibly resulted from the reaction between wollastonite, plagiocalse and quartz (reaction-2.10) along the prograde path. The presence of wollastonite and grossular in the assemblage requires a low CO_2 in the system, and hence it can be deduced that

the fluid conditions during the peak metamorphism were internally controlled. The most important reactions noticed in these calc-silicates is the partial retrogression of wollastonite and scapolite (reactions 2.1, 2. 2 and 2.3). These textures can be attributed to a later influx of carbonic fluids in these terrains during an isothermal decompressional event.

The reaction textures in the calc-silicates in the Kerala Khondalite Belt, which are reported here for the first time, require further consideration. Wollastonite -scapolite bearing assemblages are common in the southern part and marble assemblages dominate in the northwestern part of the terrain. The presence of grossular in some of the locations can be attributed to the reaction between plagioclase and wollastonite (reaction 2.4), which is characteristic of low X_{CO_2} conditions. The occurrence of wollastonite is also indicative of low CO_2 conditions prevailing during the peak metamorphic event. Hence, it is inferred that during the peak metamorphism, internally controlled fluid conditions prevailed in the terrain and that the assemblages have equilibrated at around 700°C and 5 kbar. The Kerala Khondalite Belt calc-silicates characteristically show partial retrogression of wollastonite and scapolite (Figs. 4A, B and 5A, B). This is indicative of a post peak metamorphic infiltration of carbonic fluids in the terrain (SATISH-KUMAR *et al.*, in prep.).

The characteristic silicate phases in the marble assemblages in the Kerala Khondalite Belt are phlogopite, tremolite, diopside, forsterite and spinel. These minerals have stabilised through the reactions described in this paper, most of which are low temperature reactions in low X_{CO_2} conditions and which proceed to a higher temperature with a higher X_{CO_2} in the system. These reactions proceeded with an increment to the X_{CO_2} in the system during the prograde path of the terrain, which possibly resulted in the precipitation of graphite in places where the oxygen fugacity conditions favoured. This graphite precipitation again reduced the CO_2 activity in the system which resulted in the stabilization of wollastonite.

A possible P-T evolution of the terrain is shown in Fig. 9, which indicates that the peak metamorphism occurred along with the stabilisation of the minerals such as wollastonite and grossular, and an isothermal decompression where the retrograde textures resulted. A clockwise further evolution, with very late hydrous fluid infiltration resulted in the formation of retrograde amphiboles in the assemblage. Thus, from the characteristic mineral reaction textures in calc-silicates, the pressure-/temperature-/ and fluid evolution of the terrain can be deduced.

In the Highland Complex Sri Lanka similar parageneses, reactions and textures are reported in calc-silicates and marbles. The southwestern region of the Highland Complex has wollastonite- scapolite assemblages, whereas the northern portions have higher P-T conditions, where marbles predominate (HOEFFBAUER and SPIERING, 1994). In Lützow Holm Bay also similar occurrences have been reported. It is clear, therefore, that the calc-silicates in the granulite terrains of East Gondwana comprising South India, Sri Lanka and Lützow Holm Bay in East Antarctica, have many similarities. In all these
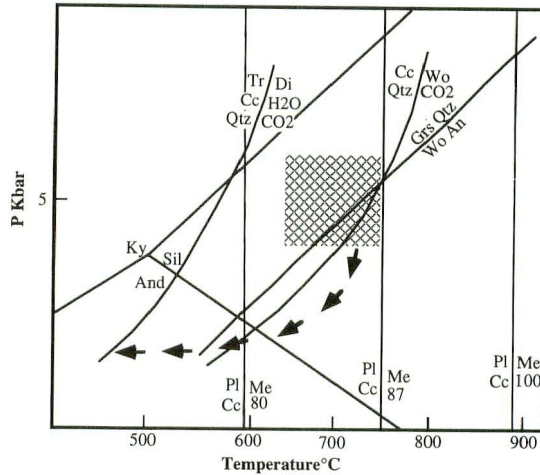
Fig. 9. P-T evolution of calc-silicates in the Kerala Khondalite Belt

occurrences, several common reactions and textures can be noticed,which indicate a comparable pressure-temperature-fluid histories of the terrain, as well as a identical post peak metamorphic evolution. In summary, the reaction textures preserved in calc-silicates of East Gondwana imply a common post-peak metamorphic history, with the terrains in Southern India, Sri Lanka and East Antarctica preserving the imprints of Pan-African rejuvenation, accompanied by an influx of carbonic fluid from sublithospheric sources. In contrast, the calc-silicates reported from Rauer Group and Prydz Bay of East Antarctica and the Eastern Ghats of India show similar assemblages and reactions which resulted from higher P-T conditions.

Acknowledgements

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