PINSA, **68, A,** No. 1, January 2002, pp. 21-34
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ULTRAHIGH TEMPERATURE METAMORPHISM IN THE EASTERN GHATS BELT, INDIA: EVIDENCE FROM HIGH Mg-Al GRANULITES

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(Received 08 August 2000; Accepted 15 February 2001)

This paper is aimed at reviewing evidence for and ultrahigh temperature ($\geq 950^0$C) of metamorphism at lower crustal depths obtained largely from high Mg-Al granulites of the Eastern Ghats Belt, India over the last decade or so. Reaction textures in a large variety of high Mg-Al granulites having different bulk rock X_{Mg}, and having equilibrated under different oxygen fugacities, are interpreted in theoretically and experimentally constructed petrogenetic grids in relevant systems. Data, leading apparently to divergent conclusions, are re-interpreted in the light of new petrographic and experimental evidence. Possible reasons for the development of anomalous high thermal gradients over the stretch of the Belt are discussed.

Key Words: Eastern Ghats Belt; Ultrahigh Temperature Metamorphism; Anticlockwise P-T Path

Introduction

In the last two decades the thermal milieu of metamorphism have been radically expanded with increasing recognition that many granulite terranes have undergone extreme P-T conditions (7-13 kbar, 900-1100°C) metamorphism. In a comprehensive review, Harley[1] showed that more than 30% of nearly 90 well-studied granulite complexes were subjected to such ultrahigh temperatures (UHT) at deep crustal levels. The number has since increased[2]. Such extreme temperatures are obviously indicative of anomalously high thermal input at the base of the continental crust, and needs to be accounted for in any model of tectonothermal evolution of the crust. Most of the clues as to UHT conditions came from the study of spinel-sapphirine-bearing high Mg-Al granulites, locally preserved in some terrain. Hensen and Green[3] in their seminal paper on experimental results in the system FeO-MgO-Al_2O_3-SiO_2 (FMAS), indicated a stability field of sapphirine+quartz at >1050°C. Despite this, UHT metamorphism was treated skeptically primarily due to the emphasis laid on temperature estimates form common Fe-Mg exchange thermometers. For UHT conditions, these thermometers will not preserve peak temperatures owing to compositional resetting during cooling[4]. Later experimental data in the system FMAS and K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (KFMASH)[5-7] corroborated the contention of Hensen and Green[3] and UHT metamorphism became a reality. Numerous theoretical analysis[8-11] and data from natural occurrences (Napier Complex, East Complex, East Antarctica[10-14]; Labwor Hills Uganda[15]; Wilson Lake, Labrador[16]; In Ouzzal, Algeria[17,18]; Gruf Complex[19]; Aldan Shield[20]; Palni Hills, India[21] have firmly established the notion of UHT metamorphism[2]. As a rule UHT condition is defined at more than 900°C at mid- to deep crustal levels[2].

The Eastern Ghats Belt (EGB) of India was known for its high Mg-Al granulite occurrences[22-25]. Dasgupta and Sengupta[26] reviewed their earlier work[27-33] and provided new evidence as well for UHT metamorphism in the EGB. Dasgupta[34] reviewed and presented a model for tectonothermal evolution of the EGB. Since then further evidence for UHT metamorphism in the EGB came from this group[35-37] as well as from others[38-40]. The purpose of the present review is to provide an updated critical analysis of the evidence, largely provided by us over the last decade from study of Mg-Al granulites, which has placed the EGB as one of the most well-studied UHT terrains[2]. The recognition of UHT meta-

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morphism in the EGB has a direct bearing on the postulated models of Indo-Antarctic correlation in the Precambrian.

Geological Background

The EGB (Fig.1) exposes a suite of very high-grade granulite facies rocks of diverse bulk composition and parentage. The dominant members are listed below.

a) Metapelitic granulites include the "khondalite" (garnet-sillimanite-quartz-perthite gneiss with or without graphite) and high Mg-Al granulites (sapphirine-spinel-garnet-orthopyroxene-sillimanite-cordierite-quartz-corundum). Locally, bands of quartzite are present in the metapelites. Mg-Al granulites occur as lenses mostly within the metapelites, but are also associated with garnetiferous quartzofeldspathic gneiss ("leptynite") and also at places as xenoliths in mafic granulites[31].

b) Quartzofeldspathic gneiss ("leptynite") with the assemblage garnet-perthite-quartz-plagioclase without sillimanite or orthopyroxene.

c) Orthopyroxene-bearing orthogneisses (including both charnockite and enderbite without sillimanite).

d) Calc silicate granulites (wollastonite -scapolite-plagioclase-grandite-calcite-clinopyroxene), mostly occurring as bands/lenses associated with metapelites.

e) Mafic granulites (orthopyroxene-clinopyroxene-plagioclase with or without garnet and minor quartz).

f) Massive and layered anorthosite complexes.

g) Alkaline rocks largely confined to the western boundary of the EGB, and

h) Acid pegmatite veins and late basic dykes.

Ramakrishnan *et al.*,[41] presented a geological map of the EGB and divided it into five longitudinal belts on the basis of lithological constitution. Dasgupta and Sengupta[42], have discussed the tectonothermal evolutionary history of the EGB (including magmatic, deformational and metamorphic histories) at length. Table I summarizes the geological history as conceived by these authors.

Table I

Event Stratigraphy of the Eastern Ghats Belt

Northern Eastern Ghats Belt
Amphibolite facies metamorphism, emplacement of pegmatites at 0.5-0.55 Ga.
Massif type anorthosites at 0.8-0.89 Ga.
M_2 granulite facies metamorphism, near isothermal decompression, cooling,
emplacement of some porphyritic granites/granitoids at c.1.0 Ga.
Alkaline magma emplacement, some basic magma emplacement, 1.5-1.2 Ga.
Intrusion of basic magma, enderbnite, M_1, UHT metamorphism (age unknown)
Southern Eastern Ghats Belt
Local resetting of Ar-Ar radioclock at 1.1 Ga.
Emplacement of pegmatite and granite along N-S shear zone at 1.65-1.5 Ga
Basic dykes Phase II
Intense crustal re-working at 1.65-1.3 Ga
Alkaline magma emplacement at. C. 1.8-1.3 Ga
Basic dykes Phase I
Intrusion of enderbitic magma
Intrusion of basic magma and UHT (10kbar,>1100°C) metamorphism followed by near isobaric cooling (age unknown).

The most confusing and the least understood component in the geological history of the EGB is the timing of the UHT metamorphism. The problem is basically related to the fact that the EGB granulites are polydeformed and polymetamorphosed (Table I). An early UHT metamorphism (M_1) culminating in near isobaric cooling was followed by a second granulite facies metamorphism (M_2), most probably of Grenvillian age (*Ca.* 960-1000 Ma), with a near isothermal decompressive retrograde path, at least three phases of deformation, and finally a Pan African (500-550 Ma) amphibolite facies overprint (M_3), hydration/carbonation and ductile shearing (Table I). As a result of later tectonothermal activities at temperatures above the closure temperatures of most of the isotopic systems, radioclocks have been reset. Although Jarreck (Unpublished Ph.D thesis, University of Muenster, Germany, 1999) claims to have dated the UHT metamorphism at Anakapalle to be 1100 Ma, the dated rocks occur as xenoliths in basic granulites, and it is thus not clear whether this age is truly representative of the regional UHT metamorphism in the EGB. Scattered isotopic evidence[43,44] suggests a distinct late Archaean age (2600-2800 Ma) for basic magmatism. If the basic magma supplied heat for the UHT metamorphism[27, 30], the latter would be Archaean itself. Without going into this controversy, we believe that the age of the UHT metamorphism is still uncertain. Further work is clearly warranted in this direction.

There are scattered isotopic evidence in favour of a spatial variation (from east to west) in the age of the rock units in the EGB as well (M Raith, Personal communication, 2000). If true, this would justify some of the longitudinal divisions of the EGB proposed by Ramakrishnan *et al.*,[41] and Mezger *et al.*,[45] and Mezger and Cosca[46], on the other hand, suggested that the rocks lying to the north of the Godavari Rift (Fig. 1), designated as NEGB, have different tectonothermal histories as compared to those occurring to the south (SEGB) on the basis of isotopic data. Therefore, there are suggestions favouring both E→W and N→S divisions of the EGB as distinct "terranes" juxtaposed together. A firm conclusion in this regard is awaited.

Ultrahigh Temperature Metamorphism in the EGB:Evidence from High Mg-Al Granulites

As in all other granulite terrains, evidence for UHT metamorphism came mainly from the high Mg-Al granulites, and was to some extent corroborated from calc silicate granulites[26,29,33], In this paper, we will restrict ourselves to Mg-Al granulites. These rocks were particularly useful in deciphering not only the peak thermal conditions, but also prograde and retrograde paths of polymetamorphism. We would focus here the M_1 UHT metamorphism as discussed before.

Preamble

Before presenting the features of UHT metamorphism in the EGB, it seems pertinent to highlight some of the key features of UHT metamorphism in general. Experimental data in the model system KFMASH has shown that at temperatures exceeding 850^0C pelites and psammopelites are expected to be partially molten[6,7,47-51]. These results also indicate that the characteristic mineralogy of the high Mg-Al granulites can be produced by dehydration-melting of a pelitic/psammopelitic protolith of biotite + quartz ± sillimanite +plagioclase between 5-10 kbar and T>850^0C Carrington and Harley[6] derived an experimentally constrained petrogenetic grid in the

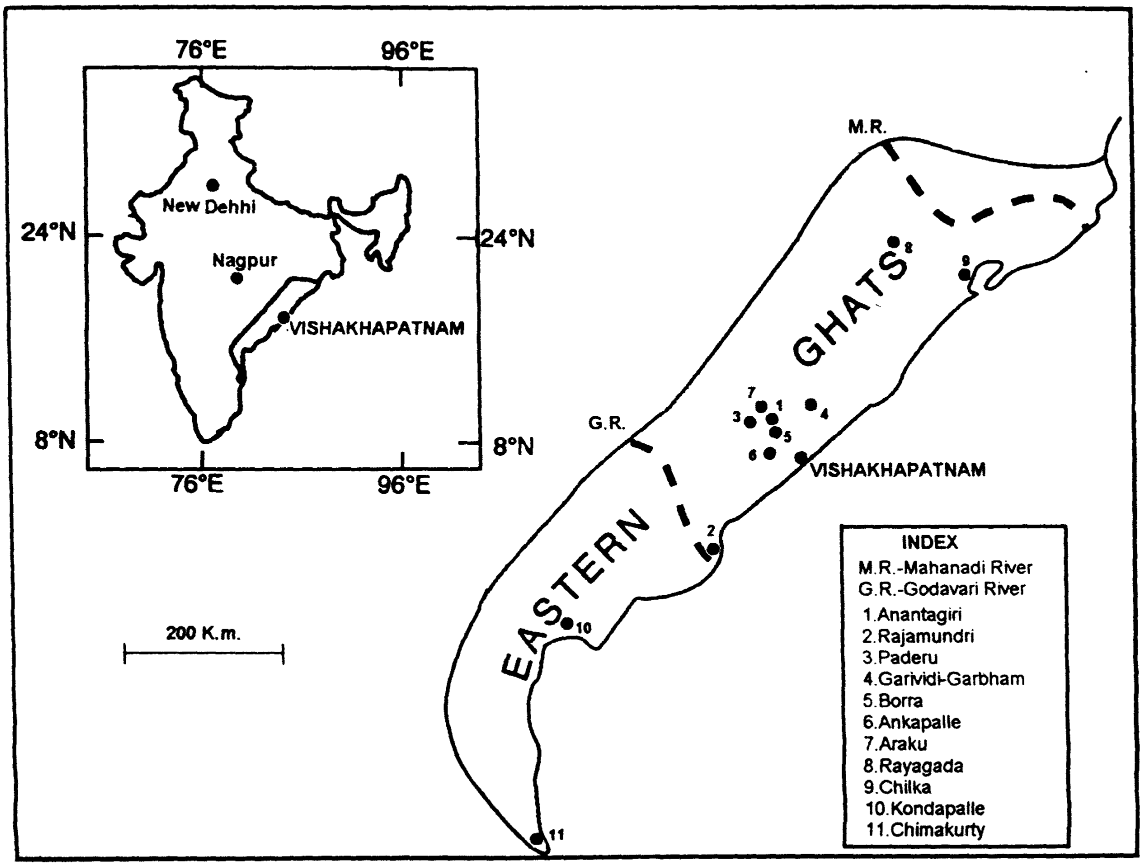

Fig. 1 Location map of the Eastern Ghats Belt showing areas of Study of Mg-Al granulites

system KFMASH (Fig. 2). The assemblages characteristic of UHT in this grid are those stabilized up-temperature of [Spr, Spl], located at 8.8 kbar, 900^{0}C. However, non KFMASH components, such as Ti, and F, which are strongly partitioned into biotite, can displace [Spr, Spl] to temperatures> 950°C. Therefore, UHT metamorphism can occur below T [Spr, Spl] under such circumstances[36]. A key UHT assemblage is osumilite + garnet stabilized in high magnesian bulk composition at T>850°C, but at P<8 kbar (Fig. 2). The experiments of Carrington and Harley[6] were carried out under QFM buffer and the results are applicable to a large number of Mg-Al granulites equilibrated at low fO_2. However, many natural assemblages equilibrated at higher fO_2 (>NNO buffer), and Dasgupta *et al.*,[32] constructed a partial

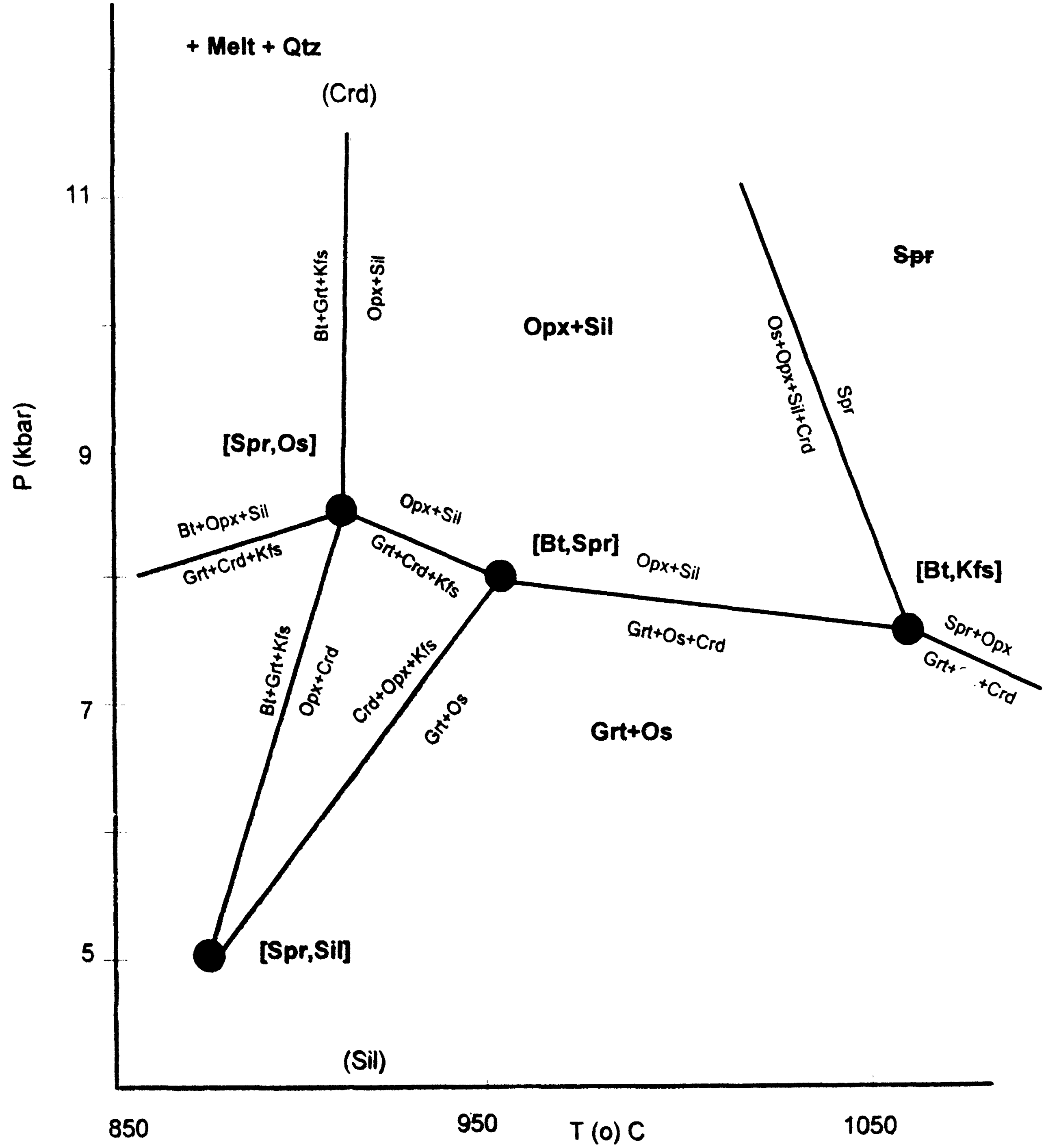

Fig. 2 An experimentally determined petrogenetic grid in the system KFMASH[6] Only the key reactions are shown for clarity

petrogenetic grid in the system KFMASH at high fO_2 (Fig. 3). The situation is analogous to that in the system FMAS[8], where two alternative grids have been constructed. Central to the problem is the stability of the assemblage spinel + quartz at high fO_2, where sapphirine + quartz is stable at low fO_2 under similar P-T conditions[52] (Figs. 4, 5). Accepting that fO_2 could indeed be a factor, Sengupta *et al.*,[28] argued that several other factors, such as X Fe in the bulk composition and presence of Zn and/or Cr, could also enlarge the stability field of spinel + quartz in natural assemblages. Nevertheless, the assemblage spinel + quarz + orthopyroxene + sillimanite, not permitted in the low fO_2 FMAS system[8], is indicative of UHT conditions at high fO_2[2, 32].

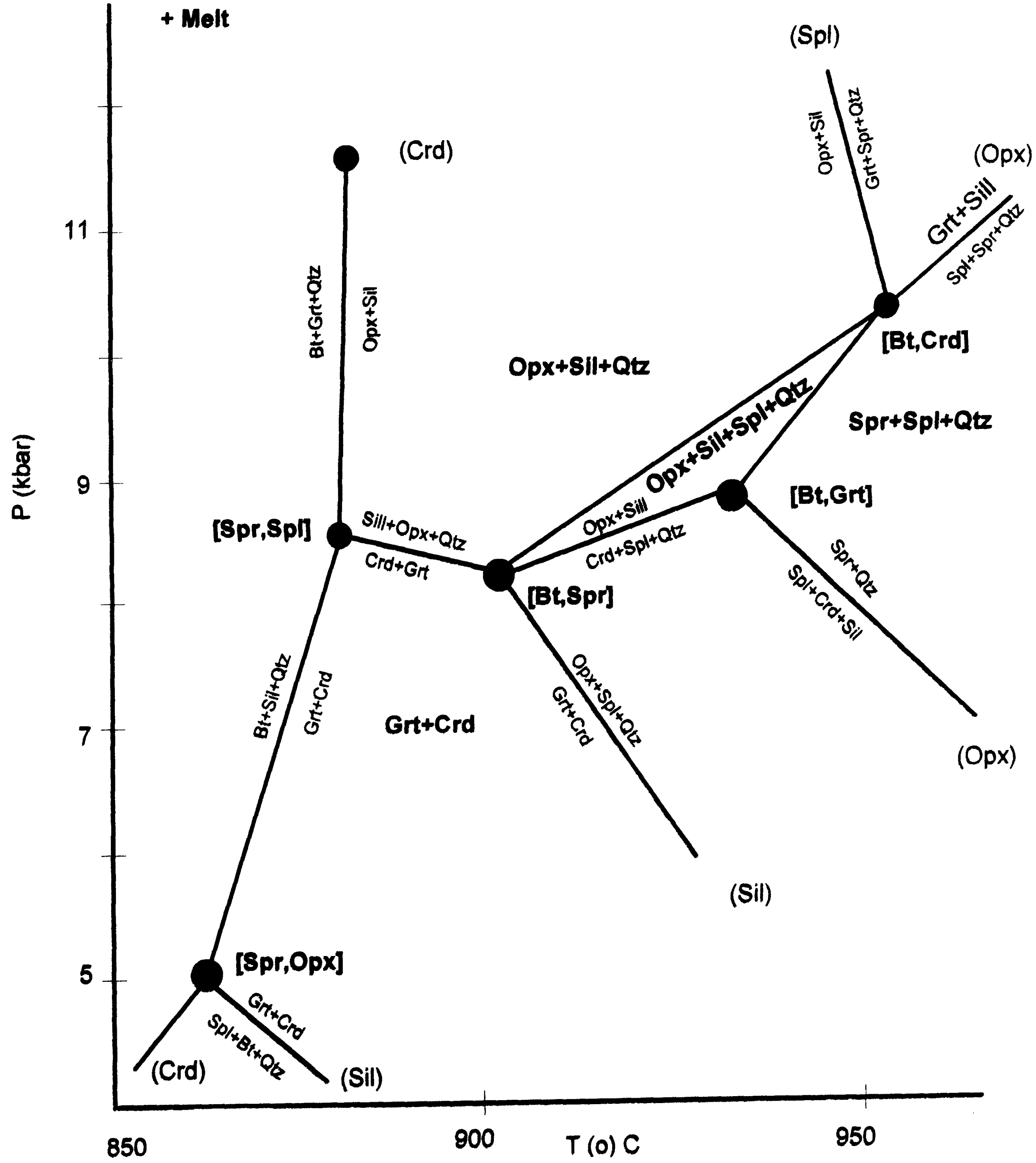

Fig. 3 A partial petrogenetic grid in the system KFMASH[32] at high fO_2 showing key UHT assemblages

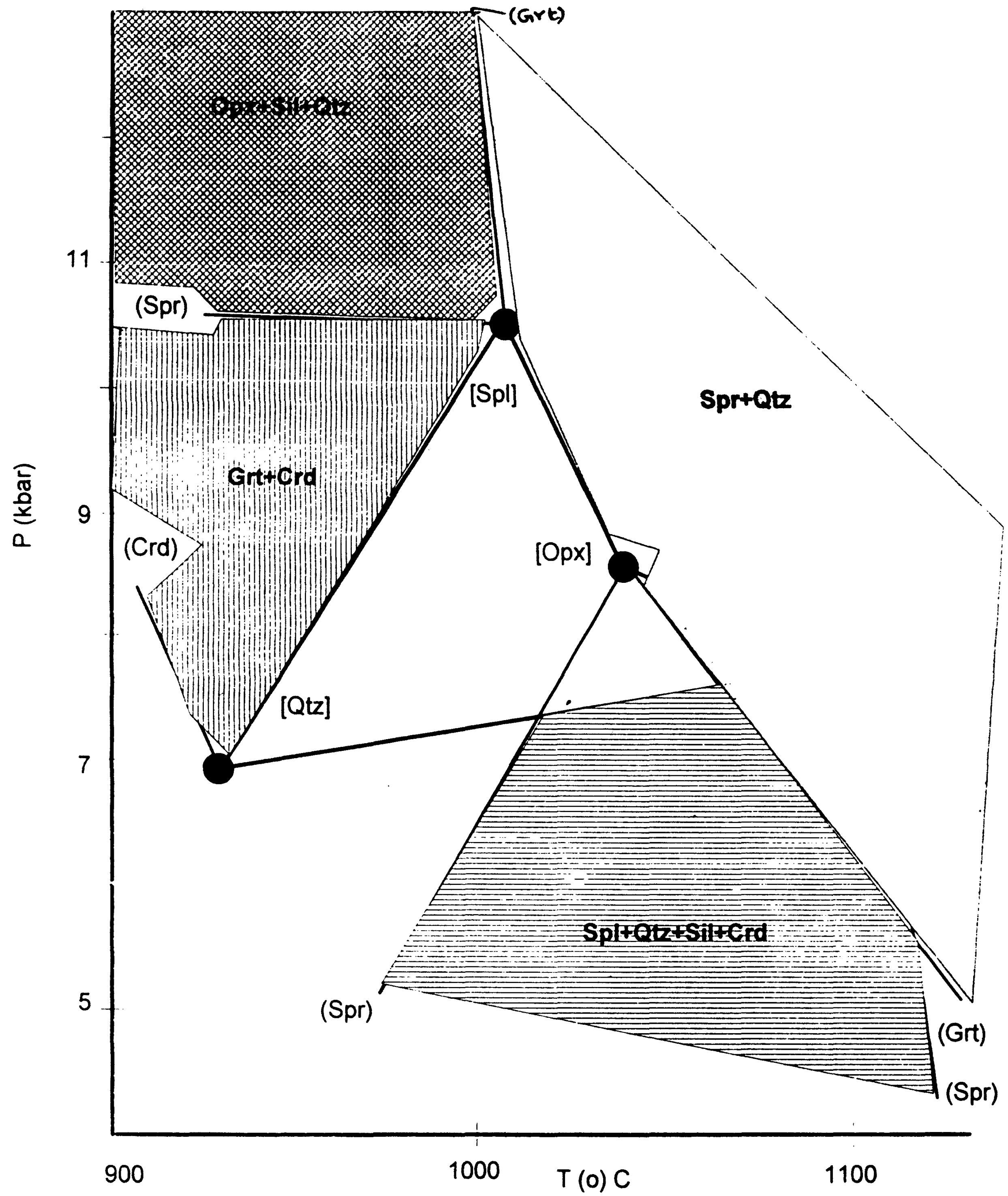

Fig. 4 A partial petrogenetic grid in the system FMAS at low fO_2 showing stability field of different assemblages. Only some key reactions are shown for clarity

Harley[2] provided another criteria of UHT metamorphism by constructing isoplethed diagrams for the phases in the system KFMASH using the experimental data of Carrington and Harley[6]. It was shown that orthopyroxene with 9-12 wt.% Al_2O_3 will coexist with garnet (X_{Mg}>0.5) under UHT conditions.

The Mg-Al Granulites from the EGB

In the backdrop of these mineralogical and chemical constraints for Mg-Al granulites, we will now examine the rocks from the EGB. Grew[22] listed occurrences of these rocks from the EGB. Fig. 1 shows the locations of the well-studied occurrences. Most

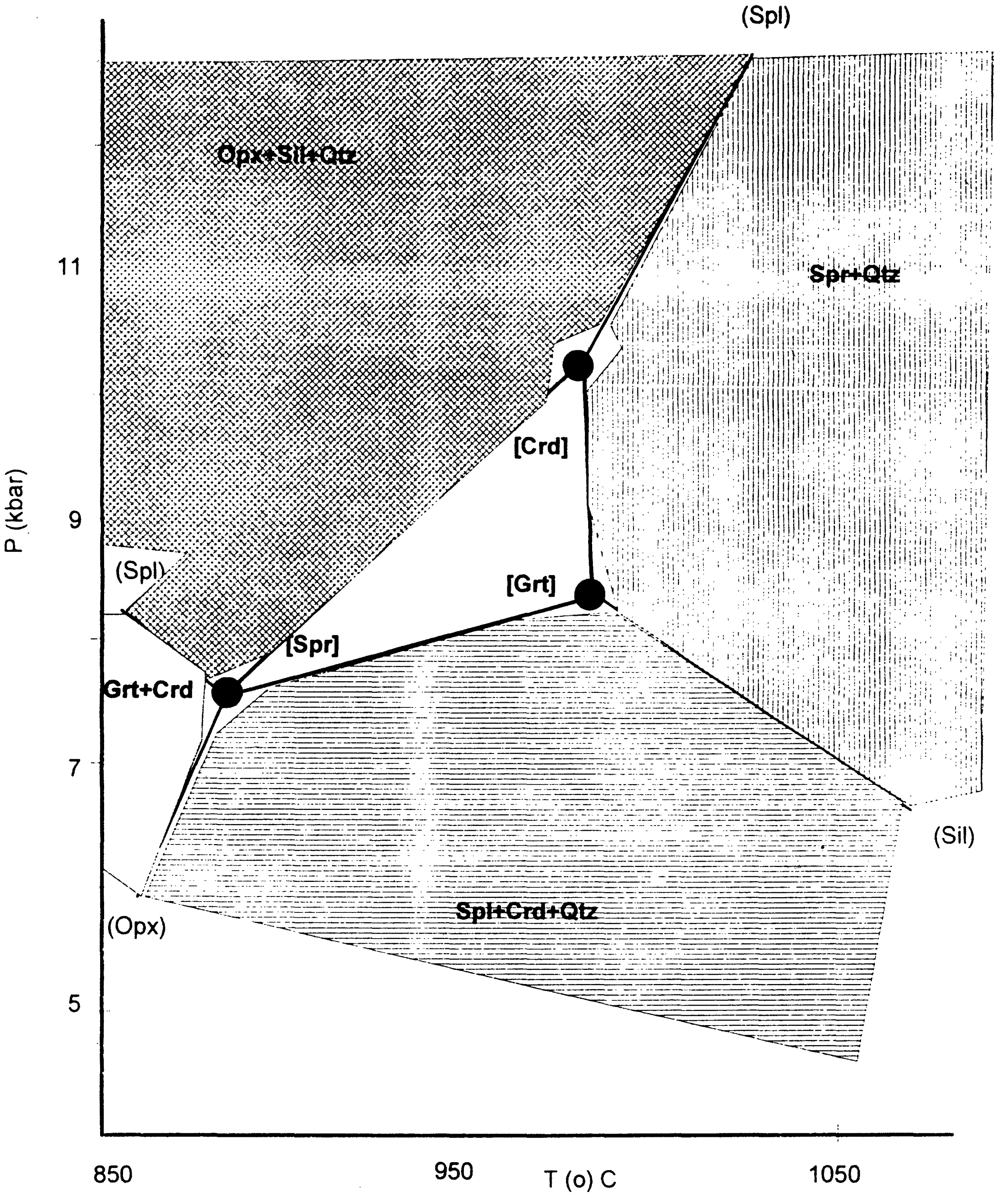

Fig. 5 A partial petrogenetic grid in the system FMAS[26] at high fO_2 showing stability field of different assemblages. Only some key reactions are shown for clarity

of these rocks are migmatitic in character with quartzofeldspathic leucosomes interpreted to be melt fractions. Lal *et al.*[23] first presented a detail account of reaction textures preserved in Mg-Al granulites from Paderu, and determined the P-T path of evolution with the help of a petrogenetic grid. There are two major problems with their interpretation. First, the grid chosen by them was topologically incorrect, and hence inappropriate for the assemblage, and secondly, they relied on cation exchange thermometry for temperature estimation[35,53]. The data of Lal *et al.*[23] when considered in the correct grid suggests UHT conditions[35]. A convincing case was presented by Kamineni and Rao[24] from Vizianagram and their deduced P-T history was corroborated by later work (reviewed in Dasgupta[34]). Their temperature estimate, however, needs to be upward revised in to the UHT regime in view of later experimental data[5,6].

Over the last decade, we have described several occurrences of Mg-Al granulites and interpreted reaction textures preserved in them in appropriate petrogenetic grids in the system FMAS and KFMASH. We examined assemblages equilibrated under both low and high fO_2 conditons, developed from relatively Mg-rich and Fe-rich protoliths in both silica-saturated and undersaturated bulk compositions, thus covering a large spectrum of variables influencing phase relations in these rocks. We have constructed several alternate petrogenetic grids to explain mineral reactions inferred on textural and compositional criteria.

Assemblages Equilibrated at Low fO_2 in High Magnesian Bulk Composition

At Anantagiri (Fig. 1) sapphirine+quartz, coexisting with rutile+ilmenite, was stabilized at perk metamorphism[27]. On textural and compositional grounds they showed that this assemblage developed from an earlier spinel+quartz + cordierite + sillimanite assemblage. Subsequent to the metamorphic peak, sapphirine + quartz gave way to orthopyroxene + sillimanite and garnet + sillimanite. When considered in the low fO_2 FMAS grid (Fig. 4), this would imply an anticlockwise P-T path of evolution culminating at T>950°C and P≅9-10 kbar, and followed by near isobaric cooling[27].

Assemblages Equilibrated at High fO_2 in High X Fe Bulk Composition

Spinel + quartz ± cordierite was stabilized in Mg-Al granulite from Araku during peak metamorphism[28]. A partial petrogenetic grid, alternative to the low fO_2 grid of Hensen[8] in the system FMAS was constructed by these authors to explain the mineral reactions. The observed topological inversion was shown to have resulted from the enlarged stability of spinel in Fe-rich bulk composition, and the reverse partitioning of Fe-Mg between garnet and spinel. This postulation was later experimentally verified by Nichols *et al.*,[54] Both petrogenetic grid consideration and thermobarometry attest to peak metamorphic conditions of 8.5 kbar, 950°C. Orthopyroxene + sillimanite + garnet were produced during post-peak near isobaric cooling.

A rather unusual sapphirine-spinel–Fe Ti oxide bearing relatively Fe-rich Mg-Al granulite was described by Dasgupta and Ehl[55]. The rock show complex intergrowth patterns between hemoilmenite-titanohematite-corundum-spinel, indicative of stabilization of an early Ti-rich aluminous spinel. Considering the experimental data in the system Fe Mg-Ti-Al-O[56,57], this alone indicates extreme high temperatures[36,58]. Spinel (Ti-rich) + sapphirine + quartz + garnet was stable during peak metamorphism (*Ca.* 10 kbar, 950°C), which gave way to garnet + sillimanite during near isobaric cooling[55].

Similar complex intergrowths of Fe-Ti-Al oxides have been reported from Kondapalle by Sengupta *et al.*,[36] which indicates early stabilization of Ti-Fe^{3+} - rich spinel. The complex oxide intergrowths developed during post-peak cooling from temperatures exceeding 1000°C. Orthopyroxene + Ti-rich spinel was stabilized during peak metamorphism in relatively Fe-rich bulk composition at high fO_2 at Sunkarameta (Fig. 1), where peak P-T conditions of 9 kbar and 950°C were estimated[37]. These rocks exhibit textures indicative of post-peak near isobaric cooling (for example, formation of coronal garnet).

Assemblages Equilibrated at High fO_2 and Derived from Mg-Rich Bulk Composition

Dasgupta *et al.*,[32] described several interesting mineral assemblages in Mg-Al granulites from Rajahmundry (Fig. 1) and constructed a partial petrogenetic grid in the system KFMASH at high fO_2 (Fig. 3). Reaction textures showed that dehydration-melting of an initial biotite-sillimanite-quartz produced spinel + cordierite + quartz ± garnet during prograde metamorphism. Spinel + quartz continued to be stable at higher temperatures in domains where the former contained Zn. This exemplifies the role of Zn in stabilizing spinel. However, in Zn-poor domains sapphirine appeared at the peak and the assemblage was sapphirine + quartz ± sillimanite ± spinel ± garnet. This assemblage, when considered in the constructed grid, defines P-T condition of 9-10 kbar, >950°C [32]. Such an extreme temperature is consistent with high (*Ca.* 10wt.%) Al_2O_3 content in orthopyroxene. Subsequent near isobaric cooling produced orthopyroxene + sillimanite.

From Paderu (Fig. 1) and adjoining areas, Sengupta *et al.*,[53] described peak metamorphic assemblage of garnet + aluminous orthopyroxene (11 wt.% Al_2O_3) + cordierie ± sillimanite ± sapphirine + osumilite in magnesian bulk composition at high fO_2. Osumilite is not preserved in this rock, but its former presence is indicated by the characteristic orthopyroxene + cordierite + K-feldspar ± quartz symplectite (also see Lal *et al.*,[23]). Sengupta *et al.*,[53] construed a P-T conditon of 8 kbar, 950^{0}C through interpretation of the reaction textures preserved in these rocks in KFMASH topology. Subsequently, near isobaric cooling produced orthopyroxene-sillimanite.

Bose *et al.*,[37] described highly aluminous (9-11wt% Al_2O_3) orthopyroxene + sapphirine + cordierite assemblage stabilized at the peak metamorphic condition (T + >950^{0}C, P-9 kbar) in magnesian bulk composition from Sunkarametta. This assemblage is in contrast with aluminous orthopyroxene + Ti-rich spinel assemblage stablized in Fe-rich bulk composition from the same are (described earlier).

Assemblages Developed from Silica-Undersaturated Bulk Composition at High fO_2

One of the mineral assemblages in the Mg-Al granulites of Kondapalle[36] is free of quartz and contains corundum. Textural relations indicate that garnet + spinel + corundum + sillimanite was stable at peak metamorphism. It is, however, likely that quartz was present initially, and was exhausted in early biotite-melting reactions. This is suggested by the presence of a few isolated inclusions of quartz in garnet. As mentioned earlier, the presence of complex intergrowths of Fe-Ti-Al oxides in this rock independently attests to an extreme metamorphic temperature (>1000^{0}C). Since there was no available petrogenetic grid in the system KFMSH at UHT conditions to explain phase relations involving both quartz- and corundum-bearing assemblages, Sengupta *et al.*,[36] constructed a new grid combining both silica-saturated and silica-undersaturated assemblages (Fig. 6). They positioned the invariant points in *P-T* space utilizing available experimental and natural rock data. They were able to delineate the stability fields of the assemblages garnet + spinel + corundum + sillimanite at P > 8.8 kbar, T > 900-1100°C, and of garnet + spinel + sillimanite + cordierite at similar T but at lower P (Fig. 6). The former stabilized at Kondapalle, attests to extreme thermal conditions. The developed grid showed that in silica-undersaturated pelites, complete elimination of Ti- and F-rich biotite would require T>900^{0}C. it was also shown that dehydration-melting of biotite+ sillimanite + quartz would produce spinel + cordierite at shallow depth and garnet + cordierite at greater depths.

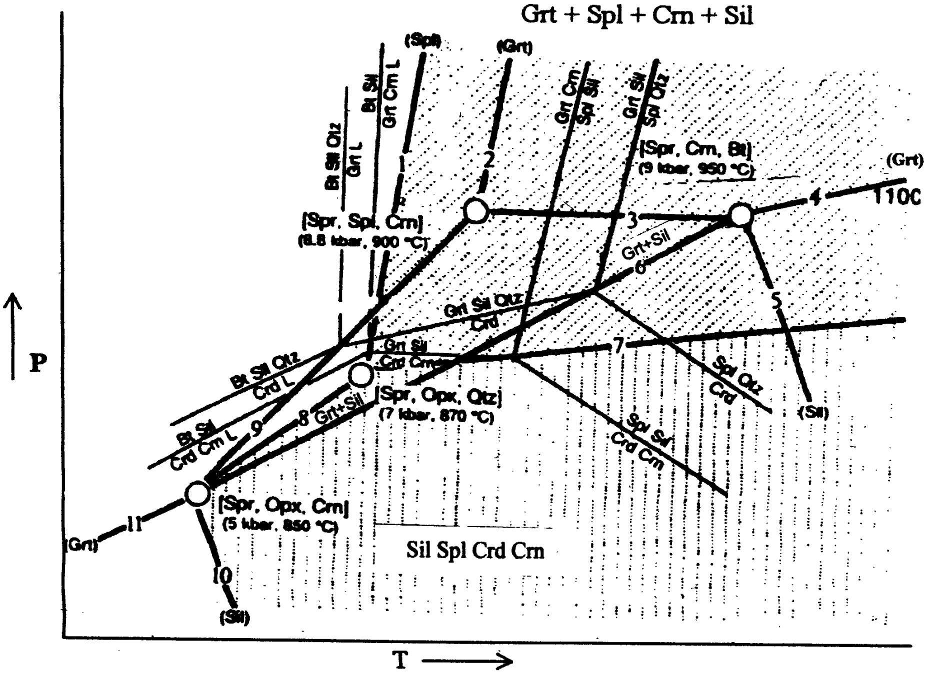

Fig. 6 A partial petrogenetic grid in the system KFMASH incorporating stability fields of assemblages in silica-saturated and silica-undersaturated bulk compositions[36]

Evidence from the Thermobarometry in Mg-Al Granulites

In recent years there have been several attempts to quantify P-T conditions of metamorphism through appropriate modification of mineralogical thermobarometers so as to make them applicable for UHT conditions. The compositional data taken by Harley[2] to prepare isoplethed diagrams is from the experimental data of Carrington and Harley[6]. Harley[2] calculated temperatures exceeding 900^{0}C using published compositional data on garnet-orthopyroxene-cordierite from the EGB. This is more consistent with estimates from petrogenetic grid considerations as discussed in preceding sections. We have plotted our data in the isoplethed diagrams of Harley[2] (Fig. 7.), and obtained temperatures exceeding 950^{0}C. Harley[2] also applied the "retrieval" method of Fizsimons and Harley[59] to calculate peak temperature for some Mg-Al granulites from the EGB and obtained similar temperatures.

Lal[60] proposed an internally consistent thermodynamic dataset for the phases in the system FMAS and calculated *P-T* for some of the Mg-Al granulites using published compositional data. The largest uncertainty in the dataset is related to natural 7:9:3 sapphirine, which obtained through empirical adjustment of experimental data on synthetic 2:2:1 sapphirine. Calculation of *P* and *T* is further problematic because of rather poorly constrained *a-x* relationships for the phases, particularly sapphirine, aluminous orthopyroxene and spinel, the last one often incorporating non-FMAS components. Finally, for any UHT assemblage, "frozen-in compositions" are not expected to be preserved due to down *P-T* adjustments, and hence, "peak" conditions are unlikely to be retrieved. This is evident from the calculated *P-T* conditions of equilibration from several Mg-Al granulites in the EGB[60,61], where the authors obtained temperatures far less than that would be required to stabilize sapphirine + quartz and Zn- poor spinel + quartz in the rocks in question. Therefore, "peak temperatures" in the tune of 950^{0}C, as calculated from thermometry, are essentially minimum estimates.

Evidence for Prograde Path of Metamorphism and Nature of the Overall P-T Trajectory for the UHT Metamorphism in the EGB

Owing to high reaction rates under UHT conditions the early metamorphic textures are nearly completely obliterated. For this reason the prograde path of metamorphism in such situations can seldom be deduced. However, we had earlier provided textural and compositional evidence in favour of an anticlockwise *P-T* trajectory, comprising an early low pressure- high temperature prograde arm culminating at P-T_{Max} of 8-10 kbar, > 950^{0}C from two occurrences of Mg-Al granulites in the EGB[27,32]. Subsequently, the rocks evolved along a nearly isobaric cooling path. The heating-cooling trajectory deduced by Sengupta *et al.,*[36] and Bose *et al.,*[37] are also anticlockwise in the sense that P_{Max} was not reached before T_{max}, although compression was not significant during prograde metamorphism. Heating -cooling trajectories are direct consequences of magma induced metamorphism[1,62] and provide clues as regards the cause of UHT metamorphism in the EGB. Geological relations in the these places, such as occurrence of Mg-Al granulites either in close association or within voluminous mafic granulites (derivative of tholeiitic magma intruded at lower crustal depths under extensional setting[63], lend credence to such a contention.

A notable exception to this deduction (that the first metamorphism in the EGB was along an anticlockwise trajectory leading to UHT) conditions during the peak and was followed by isobaric cooling) is the occurrence at Anakapalle[31,64]. Here a slight decompression in the tune of 1.5 kbar is recorded subsequent to peak metamorphism, which was *followed* by near isobaric cooling (also see Sengupta *et al.,*[53]). This occurrence is enigmatic in several senses: (a) the Mg-Al granulites occur as xenoliths in mafic granulites, (b) there is textural evidence for an earlier high *T* event[63, 31], that renders correlation with the UHT metamorphism elsewhere in the EGB problematic, and (c) a slight decompression is possible along an anticlockwise trajectory as well[1]. The prograde path of metamorphism could not be detected for the Anakapalle occurrence, and, therefore, the overall *P-T* trajectory remains indeterminate. We would, therefore, contend that until more convincing evidence is obtained the Anakapalle occurrence should not be taken as representing the general UHT metamorphism in the EGB.

Discussion

We begin with a summary of our work on the Mg-Al granulites from the EGB. We have carried out studies on Mg-Al granulites occurring over a large

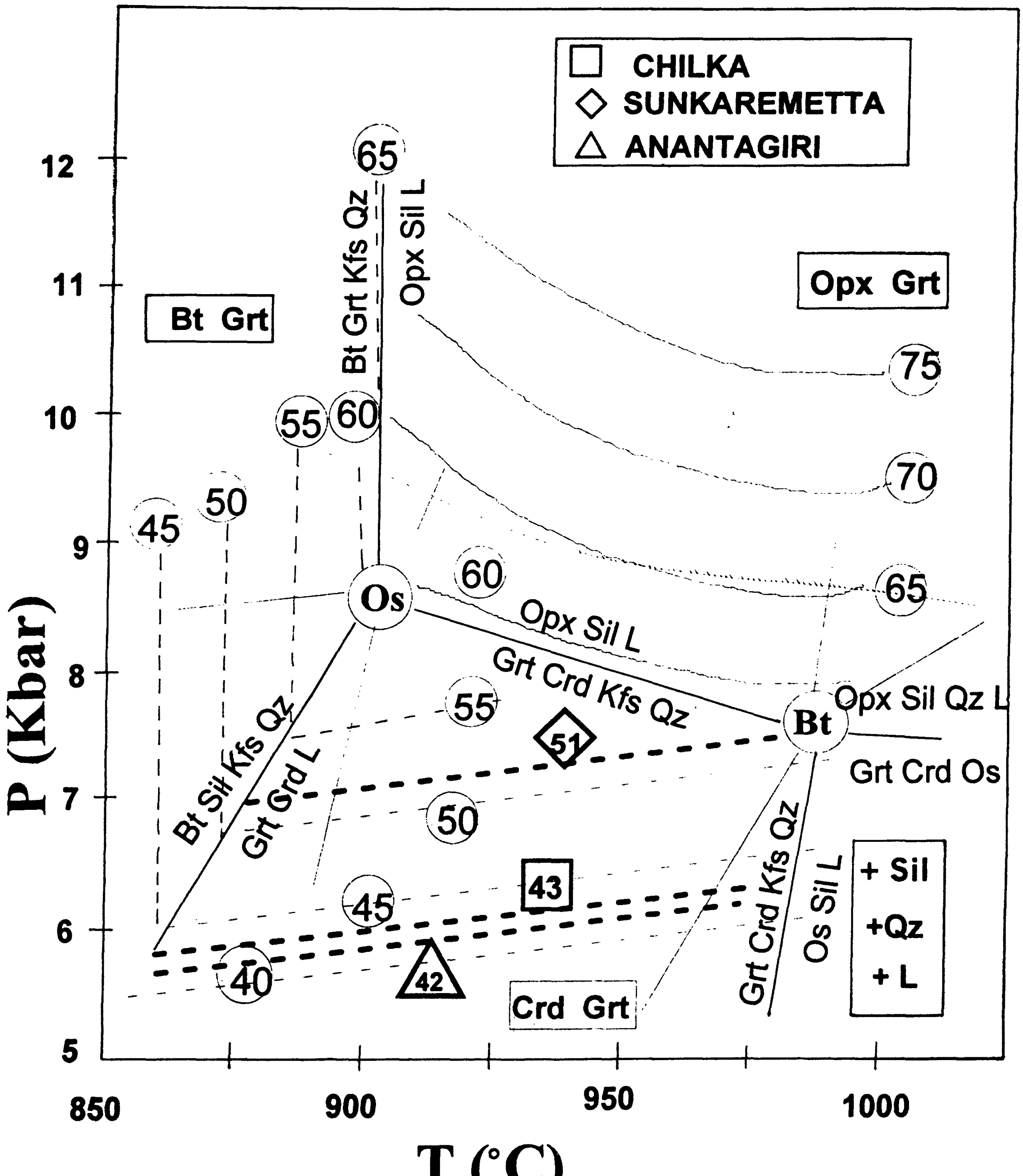

Fig. 7 Al-content of orthopyroxenes in high Mg-Al granulites from some areas in the EGB plotted in the diagram of Harley[2]. The diagram shows metamorphic temperatures in the UHT regime for the EGB granulites

tract in the EGB that covered all the subdivisions[45,46,41]. Results obtained so far brought out a coherent history of UHT metamorphism in the EGB. The Mg-Al granulites are products of dehydration melting of biotite + quartz ± sillimanite ± plagioclase bearing pelitic and locally psammopelitic protoliths having variable X Mg in the bulk, as well as silica saturation. These equilibrated under both low and high fO2 conditions. Several new partial petrogenetic grids in the system. KFMASH and FMAS were constructed to account for mineral reactions deduced from textural and compositional criteria. The commonalties deduced by us are that all these Mg-Al granulites record extreme thermal conditions (>950^{0}C) at pressures varying between 8 and 10 kbars, i.e. Corresponding to crustal depths of 27-33 km. Wherever, prograde path could be deduced, an anticlockwise P-T trajectory is indicated. Subsequent to peak metamorphism to rocks cooled nearly isobarically. As earlier mentioned, this statement pertains to the first granulite facies metamorphism in the EGB.

Evidence from Other Occurrences of Mg-Al Granulites in the EGB-Divergent Views?

Several other occurrences of Mg-Al granulites have been investigated by different workers, which apparently led to divergent opinions. In this section, we would critically examine these results. The mineral assemblages described by Kamineni and Rao[24] from Vizianagram (Fig. 1) and by Mohan *et al.*,[61] from G Madugula, very close to Paderu (Fig.1) e.g. spinel + quartz + sillimanite + sapphirine, are indicative of UHT metamorphism (>950^{0}C) in the light of experimental data discussed earlier. This was implicit in the description of the former authors. Mohan *et al.*,[61] chose to depend on poorly constrained thermobarometers that are also susceptible to resetting during cooling, and obtained lower temperatures. They also described osumilite-breakdown textures, but ignored its importance in spite of the availability of experimental data[6]. Pal and Bose[35] have discussed the problems with the interpretations of Lal *et al.*,[23] It has been shown by these authors, as well as by Sengupta *et al.*,[53] that the data presented by Lal *et al.*,[23] can be nicely reconciled with the general model of petrological evolution for the EGB proposed by us[27,32]. The interpretations of Shaw and Arima[36] on spinel granulites from Rayagada (Fig.1) are also consistent with our data in the sense that they documented UHT conditions and isobaric cooling subsequent to peak metamorphism.

Sen *et al.*,[38] working on the Chilka Lake occurrences (Fig.1) of Mg-Al granulites, proposed a multistage evolutionary model involving decompression and cooling. They deduced peak *P-T* conditions of Ca. 10 kbar, 1100^{0}C, and suggested an initial decompression to Ca. 8 kbar. There is a broad similarity in the estimated peak *P-T* conditions with those deduced by us from other areas. The peak conditions and the initial decompression as suggested by Sen *et al.*,[38] are dependent on positioning of two key mineral reactions around the invariant point [Spl] in the system FMAS.

Garnet + spinel = orthopyroxene + sapphirine ...(1)

Orthopyroxene + sillimanite + quartz = cordierite ...(2)

Experimental data places [Spl] at Ca. 10 kbar, 1050^{0}C only for fully hydrated/carbonated cordierite[5]. The characteristics of the Chilka Lake cordierite are not known and anhydrous cordierite is stable only up to 7 kbar[66]. Even if we assume that the cordierite in questions is fuild-saturated, we must take into account that location of a divariant reaction is *non-unique* in a petrogenetic grid. Reaction (2), for example, is *not necessarily* related to [Spl] only[8], and could occur at much lower *P* and *T*[27]. Secondly, reaction (1) was not documented by Sen *et al.*,[28] because relict garnet was not present in the assemblage. Sen *et al.*,[28] described textures in which dactylitic intergrowth of orthopyroxene + sapphirine occurs surrounding cordierite (their Fig. 3h), and sapphirine rims spinel against cordierite with orthopyroxene present in the domain not intergrown with sapphirine (their Fig. 3I). Garnet is nowhere present, but was conceived to be present earlier. This assemblage (E) of Sen *et al.*,[28] was shown to be the most magnesian one studied by these authors. Experimental data in the system KFMASH[6] precludes stabilization of garnet in highly magnesian bulk composition, but for at very high pressures. It is also not necessary to assume earlier presence of garnet. The textures described by Sen *et al.*,[28] could well be explained by the FMAS divariant reaction

Cordierite + spinel = orthopyroxene + sapphirine ...(3)

Therefore, there is neither textural nor compositional evidence in favour of UHT conditions at such pressures (nor of initial decompression) in the Chilka Lake Mg-Al granulites described by Sen *et al.*[28] Our unpublished textural and compositional data from the same suite of rocks do attest reaction (3).

Shaw and Arima[40] suggested the reaction corundum + quartz = sillimanite on textural criteria, such as, quartz inclusion in sillimanite and sharp mutual boundary between sillmanite and corundum (Fig. 1 d in their paper). On this basis they deduced peak *P-T* conditions of 12 kbar, 1100^{0}C and decompression to 9 kbar, 950^{0}C. Shaw and Arima (op.cit) also described complex intergrowths between hercynite-corundum-magnetite-ilmenite in adjoining rocks (Figs. 1a,1b,2a,2b), indentical to those described by Dasgupta and Ehl[55] and Sengupta *et al.*,[36] and interpreted these in terms of oxidation of a Ti-rich spinel analogous to the interpretation of the latter authors.

But for Fig. 1d, they opted for another explanation, (corundum + quartz = sillimanite), which is key to their interpretation of peak P and T and decompression. It is instructive to note that ilmenite is present with corundum in Fig.1d. This would imply that this intergrowth could have originated in the manner same as other intergrowth. Therefore, corundum and quartz need not have co-existed during peak metamorphism. Further, a peak pressure in the tune of 12 kbar would have stabilized pyrope-rich porphyroblastic garnet in Fe-rich metabasites[67], feature consistently absent in the EGB[30,63]. Summarizing, the textural features described by Shaw and Arima[40] can be explained in the manner same as Dasgupta and Ehl[36,55], and a peak pressure of 9-10 kbar at T>950^0C would suffice for the evolution of the rocks.

We would, therefore, conclude that textural and compositional characteristics of practically all the Mg-Al granulites from the EGB bring out a coherent picture of an early phase of UHT metamorphism (>1000^0C) at 8-10 kbar pressure, followed by near isobaric cooling.

Probable Cause of the UHT Metamorphism

Attainment of temperatures exceeding 950^0C at crustal depths 27-33 km in the EGB signifies advective heat supply through basic magma under-intraplating[68,69] or lithospheric thinning[70] with or without crustal extension[71]. This is consistent with an anticlockwise *P-T* trajectory deduced for the UHT metamorphism in the EGB. Thermal modelling for overthickened crust (typical clockwise path of England and Thompson[72]) shows that such UHT conditions at 8-10 kbar can not be achieved due to increased radiogenic heat generation, even when supplemented by heat input from CO$_2$-rich fluid fluxing[73]. UHT conditions were reached all over the EGB on a regional scale (Fig. 1). From this Dasgupta[34] concluded that lithospheric scale thermal perturbation was possibly responsible for the UHT metamorphism. This could be further aided by basic magma under-intraplating. The latter possibility gains ground from two newly studied occurrences[36-37], where both field relations (e.g. occurrence of Mg-Al granulites with voluminous magmatic rocks), and *P-T* path (heating-cooling trajectory) indicate that magmatic heat input could indeed be important. In this case the EGB granulites are the products of a "regional scale contact metamorphism at lower crustal depths". This conclusion is, of course, dependent on the age of UHT metamorphism and that of emplacement of magmatic rocks. In spite of tremendous effort by several groups of researchers (including our own), a firm answer to both the questions is awaited.

Acknowledgements

The authors would like to place on record that the appreciation have gained considerably from discussion with Prasanta Bhattacharya, Michael Raith, Masato Fukuoka, Stephan Hoernes, Klaus Mezger and Masaru Yoshida on different issues. The authors also thank S Karmaker, S K Bhowmik, S Sanyal, J Sen, U K Bhui, S Bhattacharya, S Pal, Pranesh Sengupta, S Bose and B Spiering for support at many stages of the work during the last decade. Help received from A Gangopadhyay, S Sarkar and N Datta during preparation of the paper is acknowledged. Council of Scientific and Industrial Research and Department of Science and Technology supported research through sponsored projects. The authors further would like to acknowledge support from the Alexander von Humboldt Stiftung and Deutsche Forschungsgemeinshaft.

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