9. Prezbindowski, D. R. and Larese, R. E., *Geology*, 1987, **15**, 333–336.
10. Crawford, M. L., in *Short Course in Fluid Inclusions: Application to Petrology* (eds Hollister, L. S. and Crawford, M. L.), Mineral Assoc., Canada, 1981, vol. 6, pp. 157–181.
11. Bodnar, R. J., *Geochim. Cosmochim. Acta*, 1993, **57**, 683–684.
12. Roedder, E., in *Handbook of Stratabound and Stratiform Ore Deposits* (ed. Wolf, K. H.), Elsevier, Amesterdam, 1976, pp. 67–110.
13. Johannes, W., *N. Jb. Min. Abh.*, 1970, **113**, 274–325.
14. Phol, W., *Geol. Rund.*, 1990, **79**, 291–299.
15. Gregg, J. M., *Geology*, 1985, **13**, 503–506.
16. Amthor, J. E. and Friedman, G. M., *Sedimentology*, 1991, **38**, 343–362.
17. Velasco, E., Pesquera, A. and Olmedo, F., *Min. Deposita.*, 1987, **22**, 33–41.

ACKNOWLEDGEMENTS. We thank Dr V. C. Thakur, Director, Wadia Institute of Himalayan Geology, Dehra Dun for encouragement and permission to publish this work. Thanks are also to Dr M. S. Anantharaman, Head, Geology Department, DBS College for encouragement.

Received 24 December 1996; revised accepted 19 September 1997

A new sapphirine occurrence from Kambam valley, Tamil Nadu and its possible relation to the Pan-African tectonothermal event

K. Francis Anto, A. S. Janardhan and P. Sivasubramanian*

Department of Geology, University of Mysore, Manasagangotri, Mysore 570 006, India
*Department of Geology, VOC College, Tuticorin 628 008, India

Petrography and metamorphic conditions of a new sapphirine-bearing assemblage from Kambam valley are described. Temperature of formation of sapphirine-bearing assemblages is high, around 850°C, and pressures range from 7.5 to 5 kbars, suggesting that sapphirine formation took place during decompression events.

The sapphirine occurrence of the Kambam valley is the southern most, reported so far in the southern granulite terrain (SGT). Here we report the sapphirine occurrences of the eastern Kodaikanal ranges cluster around the Kambam fault, which hosts carbonatite. In addition, numerous syenite bodies and alkaline granites are common to the Kodaikanal ranges. The age of garnet separates (Sm–Nd garnet/whole rock) of Kambam valley and Kodaikanal ranges is around 550 to 520 Ma. This indirectly gives the age of sapphirine formation, as sapphirine develops after garnet. The age of the carbonatite, syenite bodies and alkali granites which occur along these intra-cratonic lineaments ranges between 790 and 550 Ma. The close spatial association of the high temperature sapphirine-bearing assemblages with the Kambam fault strongly suggest that their formation is closely linked to Pan-African tectonothermal event.

In this paper, we report sapphrine-bearing assemblage from a new locality, south of the Kodaikanal ranges. This locality lies in the Kambam valley and is the southernmost sapphirine occurrence so far recorded from southern India. However, this sapphirine assemblage can be tied up with the numerous sapphirine occurrences from the eastern Kodaikanal ranges. Stress is laid on the tectonic significance of these sapphirine occurrences restricted to a rather narrow zone; the timing of sapphirine formation and the possible heat source.

The South Indian granulite terrain can be broadly subdivided into a late Proterozoic (Pan-African) southern granulite terrain (SGT) and late Archaean northern granulite terrain (NGT) with the fundamental Palghat–Cauvery break, now a graben, separating the two. The SGT is dominated by granulite grade supracrustal units, in addition to the normal charnockite and two pyroxene granulites. These litho units contain critical mineral assemblages which are excellent tools in constraining the metamorphic conditions and P–T–t paths. High temperature (900°C) silica-deficient sapphirine granulites have been reported from several localities in SGT, viz. Ganguvarpatti[1–3], Panrimalai[4], Perumalmalai[5–7] and Usilampatti[8].

The wedge-shaped Kambam valley is bordered by the Cardamom hills to the west and the Varushanad hills to the east (Figure 1). This valley, the resultant of a deep fault (the Kambam fault) trends in a NNE to NE direction. As can be seen from the map, the Kambam fault cuts across the eastern Kodaikanal ranges and extends further northward across the Kadavur massif anorthosite body of Proterozoic age.

The dominant rock types of the area include granulite grade pelitic and calc-silicate lithologies, interbedded with pyroxene granulite bodies amidst quartzofeldspathic charnockites. The terrain as a whole is punctured by several granite bodies. Presence of syenite and late carbonatite intrusives is significant.

Pelitic lithologies include both silica saturated (grt–cord–bt–sil) and silica undersaturated (spr–crd–opx–bt–spl–plag) varieties. Calc-silicate lithologies are intimately intermixed with pyroxene granulite bodies on a decimeter scale and contain wollastonite–scapolite–garnet–clinopyroxene associations. Charnockite is normally devoid of garnet. The present study focuses on the silica-deficient sapphirine-bearing assemblages.

Silica-deficient pelitic granulites occur as *in situ* outcrops of a few meters amidst charnockite. Pelitic and calc-silicate bands can be seen in the vicinity. Two distinct mineral assemblages, viz. spr–crd–opx–bt–spl (sapphirine present) and crd–opx–bt–plag (sapphirine absent) are noticed. Sapphire blue sapphirine and the indigo blue cordierite grains (up to 0.8 cm across) can be noticed even in hand specimens. Orthopyroxene and biotite define the regional foliation (NE-SW) and sapphirine grains often athwart the foliation suggesting that sapphirine is late.

Sapphirine is strongly pleochroic in shades of blue and green and is commonly intergrown with cordierite (Figure 2 *a*). Occasionally, sapphirine contains inclusions of spinel (XMg 0.70), cordierite and rare, calcic plagioclase. Sapphirine also occurs as slender ribs growing across orthopyroxene plates (Figure 2 *b*). At places, sapphirine is found in complex intergrowth with orthopyroxene, cordierite and biotite. Chemically the sapphirines of Kambam plot between 221 and 793 in the (MgO + FeO)–Al_2O_3–SiO_2 diagram (Figure 3). XMg varies from 0.87 to 0.91 which is slightly higher when compared to sapphirines from other localities (XMg 0.73–0.87) in the eastern Kodaikanal ranges.

Two generations of cordierite can be identified. Cordierite included in sapphirine represents the first generation (crd1). In sapphirine-absent assemblage, spectacularly large (0.8 cm long and 0.5 cm across) cordierite (crd1) has inclusions of biotite and corona of orthopyroxene. Cordierite intergrown with sapphirine, orthopyroxene and biotite forms the second generation (crd2). The two generations of cordierite have similar chemistry. Cordierite of different generations with similar chemistry has been reported from Napier complex, Antarctica and this phenomenon has been attributed to the retrograde Mg–Fe re-equilibration[9,10]. XMg value is around 0.95 and is comparable with those from other sapphirine localities in the SGT.

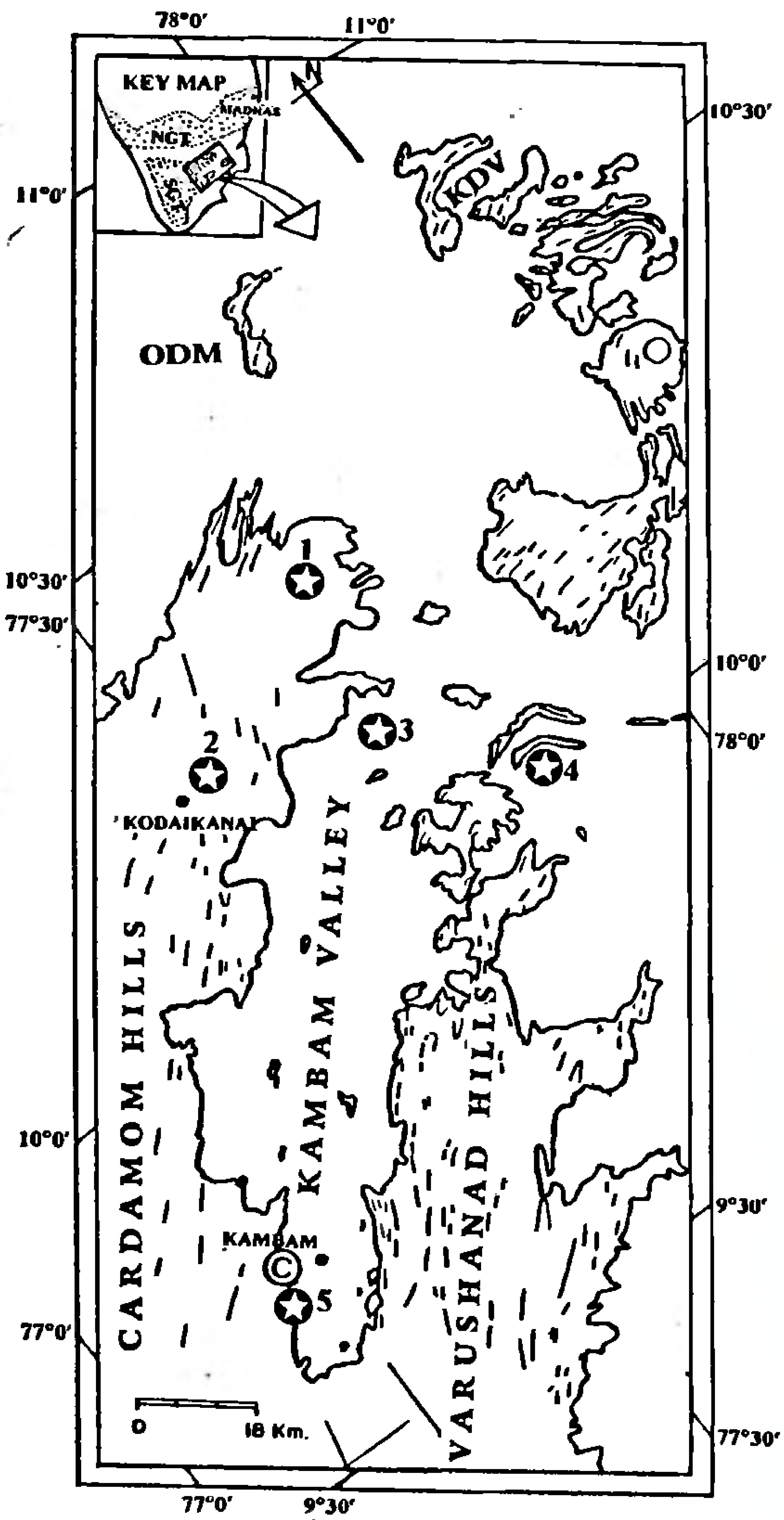

Figure 1. Map of the Kodaikanal ranges showing the different sapphirine localities: 1, Panrimalai; 2, Perumalmalai; 3, Ganguvarpatti; 4, Usilampatti; 5, Kambam; C, Kambam carbonatite; ODM & KDV, Oddanchatram & Kadavur massif anorthosite bodies. Inset – Key map; NGT, Northern granulite terrain; SGT, Southern granulite terrain.

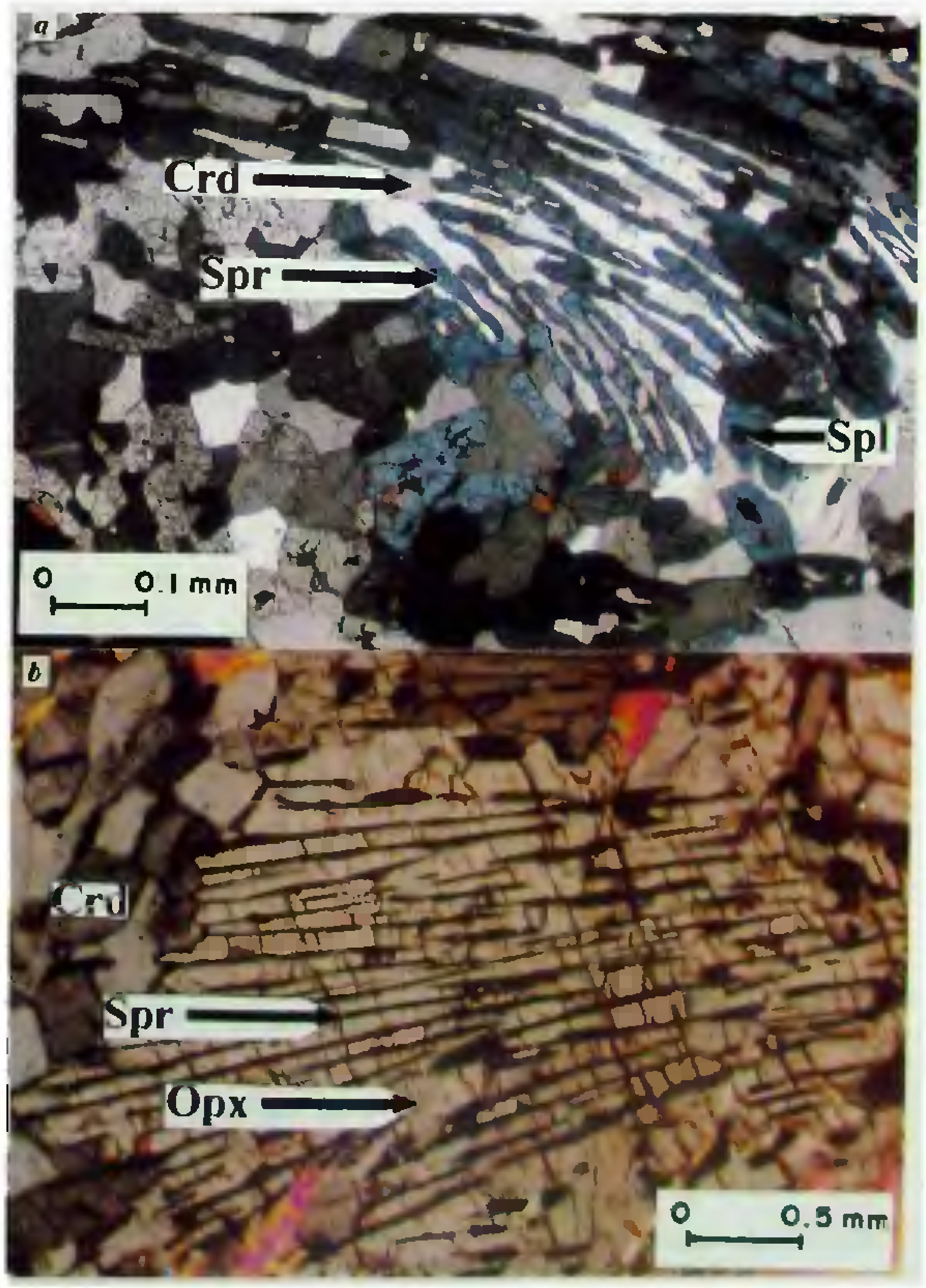

Figure 2. *a*, Photomicrograph showing sapphirine + cordierite intergrowth. Note included spinel (dark) in sapphirine (Spr). *b*, Sapphirine ribs in large platy orthopyroxene. Surrounding the orthopyroxene cordierite grains are seen.

Strongly pleochroic orthopyroxene commonly occurs as intergrowths with sapphirine and biotite. Orthopyroxene which co-exists with biotite parallels the regional foliation. They are well preserved in microdomains where sapphirine has not developed, as later sapphirine growth disrupts them.

In the present locality, orthopyroxene with 5% alumina is common and orthopyroxene with high alumina contents (8–12%) is not noticed. High alumina orthopyroxene has been reported in sapphirine assemblages from Perumalmalai[5,7] and Ganguvarpatti[3]. It is noteworthy that these high alumina orthopyroxenes with patches of sapphirine and green spinel are commonly found as breakdown product of garnet. In the above two areas large plates of orthopyroxenes with a lower alumina content (5%) also occur surrounding cordierite–sapphirine symplectites (see photographs in ref. 5). Absence of high alumina orthopyroxene in sapphirine-bearing assemblages in the Kambam locality may be because of their resorption during sapphirine formation.

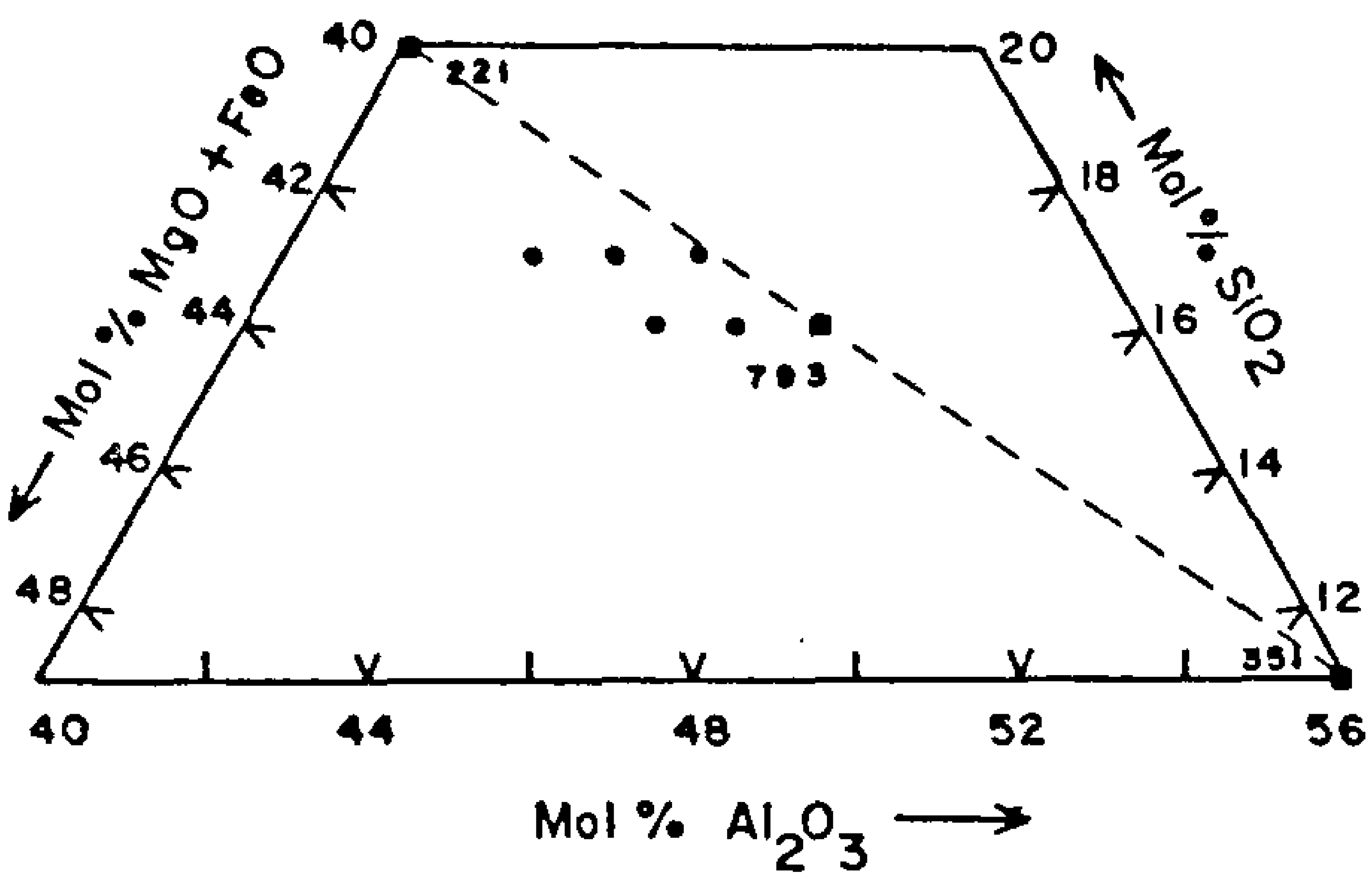

Figure 3. (MgO + FeO)–Al_2O_3–SiO_2 diagram showing the composition of Kambam sapphirines intermediate to 221 and 793.

Biotite is the most dominant mineral making up to 60% modally. Two generations of biotite which differ in texture and chemistry are identified. The prograde biotite (bt1) occurs as inclusions in cordierite or as laths defining foliation. They have higher TiO_2 content (3.5–4%). Second generation biotite (bt2) forms as an alteration product of orthopyroxene along its margin and has lower TiO_2 content (1.5–2%).

Table 1 gives the representative analyses of sapphirine, cordierite, orthopyroxene, biotite and spinel.

The assemblage sapphirine–cordierite–orthopyroxene–biotite–spinel falls within the KFMASH system. The representative mineral analyses are plotted in the trilinear diagram with apices SiO_2-6(K_2O + Na_2O), (FeO + MgO), (Al_2O_3–Cr_2O_3–Fe_2O_3), (Figure 4). Mineral reactions are deduced from textural relations in conjunction with the above phase diagram.

Table 1. Representative mineral analyses of sapphirine-bearing granulites. Sapphirine recalculated on the basis of 10 oxygen atoms; orthopyroxene, 6 oxygen atoms; cordierite, 18 oxygen atoms; spl, 4 oxygen atoms and biotite, 22 oxygen atoms

	1 spr	2 spr	3 spr	4 opx	5 opx	6 crd	7 crd	8 spl	9 bt1
SiO_2	13.66	13.88	14.24	54.77	55.66	49.50	49.63	0.06	39.14
TiO_2	0.04	0.04	0.06	0.07	0.08	0.01	0.02	0.04	3.62
Al_2O_3	62.66	63.29	61.55	5.40	4.96	33.73	34.05	65.26	16.28
FeO	3.38	3.16	3.35	6.94	6.85	0.96	0.97	14.74	5.24
MnO	0.01	0.01	0.06	0.09	0.08	0.03	0.01	0.04	0.00
MgO	19.46	18.96	19.55	32.51	32.87	12.91	12.70	19.43	20.85
CaO	0.04	0.01	0.01	0.07	0.06	0.03	0.01	0.00	0.00
Na_2O	0.00	0.02	0.02	0.01	0.01	0.22	0.11	0.00	1.07
K_2O	0.01	0.01	0.00	0.02	0.00	0.01	0.00	0.01	8.06
Cr_2O_3	0.19	0.10	0.04	0.00	0.00	0.00	0.01	0.07	0.05
Total	99.45	99.49	98.88	99.88	100.57	97.40	97.51	99.65	94.31
Si	0.802	0.813	0.840	1.893	1.908	4.978	4.980	0.002	5.584
Ti	0.002	0.002	0.003	0.002	0.002	0.001	0.002	0.001	0.388
Al	4.338	4.368	4.281	0.220	0.200	3.999	4.028	1.960	2.738
Fe	0.166	0.155	0.165	0.201	0.196	0.081	0.081	0.314	0.625
Mn	0.000	0.000	0.003	0.003	0.002	0.003	0.001	0.001	0.000
Mg	1.703	1.654	1.719	1.674	1.679	1.935	1.899	0.738	4.433
Ca	0.003	0.001	0.001	0.003	0.002	0.003	0.001	0.000	0.000
Na	0.000	0.002	0.002	0.001	0.001	0.043	0.021	0.000	0.296
K	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.000	1.467
Cr	0.009	0.005	0.002	0.000	0.000	0.000	0.001	0.001	0.006
Total	7.023	7.001	7.017	3.996	3.990	11.044	11.015	3.017	5.537
XMg	0.911	0.914	0.912	0.893	0.895	0.960	0.959	0.701	0.876

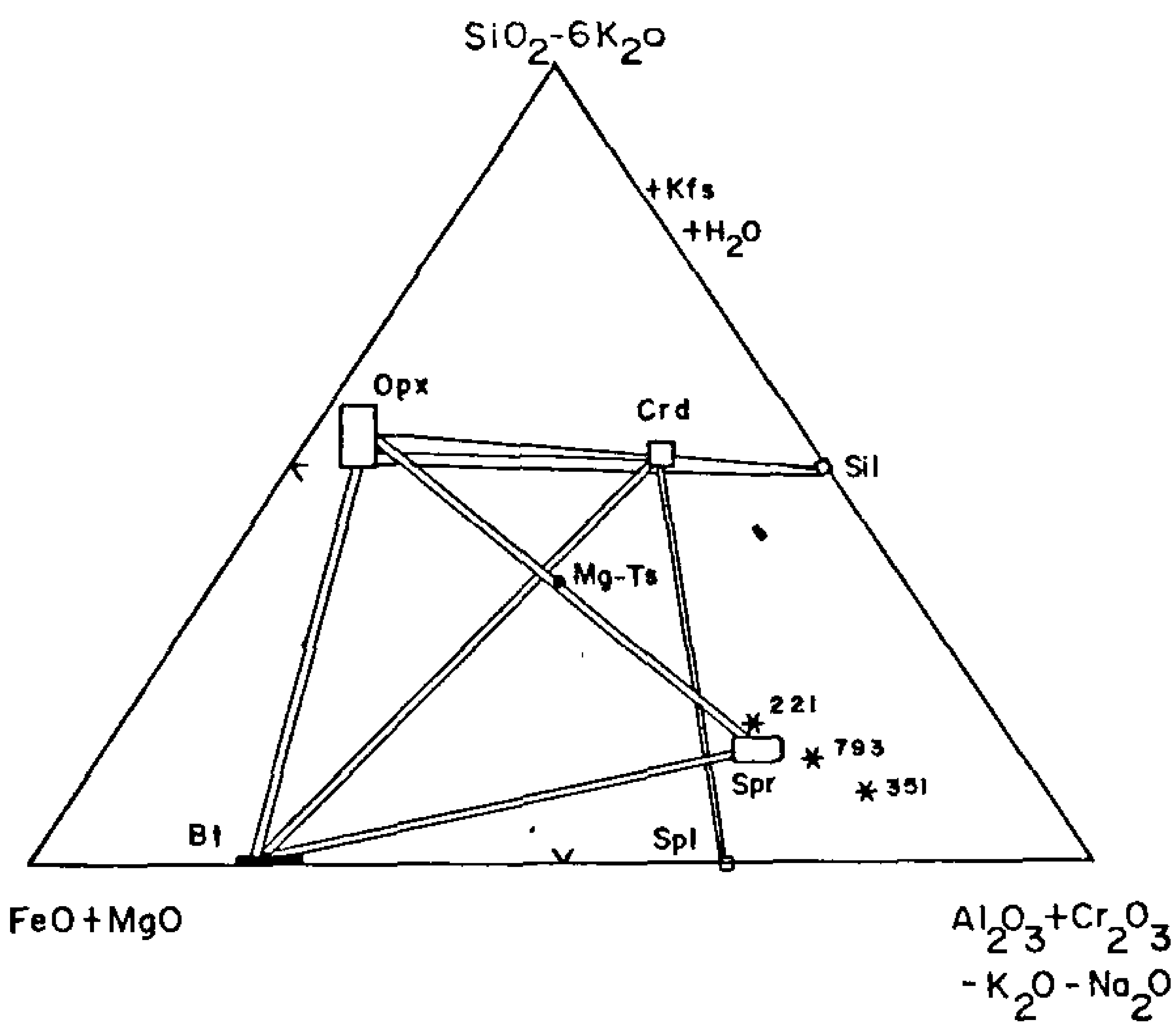

Figure 4. $(MgO + FeO)-(Al_2O_3 + Cr_2O_3-K_2O + Na_2O)-(SiO_2-6K_2O)$ diagram showing the phase relations for the sapphirine assemblage of Kambam. Projection from potash feldspar is preferred as the paragenetic relation between cordierite and orthopyroxene can be better represented unlike in AKF diagram, where they fall on the same line.

Inclusions of biotite in orthopyroxene and cordierite suggest their formation by the prograde reactions:

$$Bt + qtz \Rightarrow Opx + Kfs + V \qquad (1)$$

$$Bt + Sil + Qtz \Rightarrow Crd + Kfs + V \qquad (2)$$

In general, formation of sapphirines in eastern Kodaikanal ranges, especially in the Perumalmalai and Ganguvarpatti localities, can be explained by the following reactions:

$$Grt \Rightarrow Spr + Opx + Crd \qquad (3)$$

$$\text{Mg Tschermark of Opx} \Rightarrow Opx + Spr \qquad (4)$$

$$Spl + Crd \Rightarrow Spr + Opx \qquad (5)$$

$$Bt + Crd \Rightarrow Opx + Spr. \qquad (6)$$

Reactions (5) and (6) pertain to the present locality as can be seen from the topology of KFMASH diagram. Presence of inclusions of spinel and cordierite in sapphrine and the complex intergrowth of sapphirine, orthopyroxene, cordierite and biotite confirms the above reactions. Though garnet and high alumina orthopyroxene ($\simeq 9\%$) seem to be absent in the present locality, reactions (3) and (4) inferred as sapphirine–orthopyroxene–cordierite intergrowths are common. It is quite probable that these terminal reactions have proceeded to near completion, consuming all the garnet and high alumina orthopyroxene. More important is that, these sapphirine-forming reactions are decompression reactions.

Estimates of temperature for sapphirine-bearing granulites using spinel–cordierite[11] and orthopyroxene–biotite pairs[12,13] are 950°C and 800–830°C respectively. These values agree with the estimates using garnet–cordierite and garnet–biotite pairs of pelites and garnet–orthopyroxene–plagioclase–quartz of charnockites of Kambam valley (850–950°C). Thus, the area in general has witnessed a dominant high temperature granulite grade metamorphism.

Pressures are deduced from spinel–cordierite–orthopyroxene–biotite assemblage using TWEEQU program[14]. The pressure estimated using inclusion phases in sapphirine-like spinel, cordierite and biotite gives a maximum of 7.5 kbar, while that deduced from phases co-existing with sapphirine is lower around 5 kbar, suggesting that sapphirine formation was associated with decompression events. These pressure estimates are in good agreement with those obtained from garnet-bearing pelitic and charnockite assemblages of the area (5–8 kbar). The pressure estimates for garnet-bearing sapphirine assemblages of Kodaikanal ranges are only slightly higher (8–5 kbar)[3,5,7].

From petrography and mineral reactions, it is clear that the formation of orthopyroxene and sapphirine in Kambam valley and in general in the Kodaikanal ranges is at the expense of garnet. In garnetiferous two pyroxene granulites and charnockites, the garnets often breakdown to form orthopyroxene–calcic plagioclase symplectites. We stress on this aspect as the garnets from the charnockite and pyroxene granulite bodies of Palni ranges forming the eastern part of the Kodaikanal ranges give ages of 550 Ma and 520 Ma, respectively[15]. In the present locality, garnet separates from charnockites give ages of *ca* 520 Ma by the Sm–Nd garnet/whole rock method (Janardhan and Peucat, pers. comm.; the work was carried out in the University of Rennes, labs). We are aware of the fact that these ages represent cooling ages, and not the actual age of garnet formation. For the present study, what is important is that the dominant granulite metamorphism in the SGT is around 550 Ma, given by garnet in charnockites which does not show any symplectitic breakdown[15] and by other methods[16]. Sapphirine formation should have taken place slightly later than 550 Ma.

Kambam carbonatite gives an age of around 520 Ma by Sm–Nd and Rb–Sr whole rock methods (Anil Kumar, unpublished data). This 520 Ma age could possibly be a metamorphic age. We make this statement since the ages of carbonatites of Tamil Nadu (Sevattur, Pakkanadu localities) are around 790 Ma (ref. 17). The age of Munnar alkaline granite of 740 Ma (ref. 18) is significant. The age range of 800–550 Ma is commonly described as Pan-African events elsewhere[19].

The age of sapphirine formation in the Eastern Ghats is suggested to be around 1000 Ma (ref. 20). Recent ages of 950 Ma (ref. 21) for the granulite event of the

Eastern Ghats support the above data. Thus, sapphirine formation in the Eastern ghats and in the SGT probably took place at different times and this has a great bearing on the tectonic evolution of these two granulite terrains.

From Figure 1, it can be seen that all the sapphirine localities from eastern Kodaikanal ranges cluster around the Kambam fault extending from Kambam and cutting across the eastern Kodaikanal ranges. The present carbonatite and sapphirine locality lies at the southern extremity of the Kambam fault which trends in a NNE to NE direction.

It is to be noted that in northern Tamil Nadu, the carbonatite–syenite associations also occur along NNE trending major faults[22]. Hence, Kambam fault is comparable to the above major faults and sapphirine formation is closely linked to the Pan-African rifting and high temperature magmatism.

Thus, the present study describes a new sapphirine occurrence from Kambam valley which forms part of the SGT. This study also brings out the fact that most of the sapphirine assemblages of the Kodaikanal ranges, including the well-described Ganguvarpatti and Perumalmalai ones occur in a rather narrow tract, paralleling the NNE trending Kambam fault. The other well-known reports of Kiranur, Ellamankovilpatti and the Sittampundi also occur in the Palghat–Cauvery fundamental break.

The Kambam fault is akin to the major NNE trending deep crustal faults in northern Tamil Nadu and can be extended further northward to the Attur fault zone of Grady[22], which lies east of Tiruvannamalai. Incidentally, sapphirine-bearing assemblages have also been reported from Ponnakadu, 7 km west of Tiruvannamalai[2]. Carbonatite–syenite–shonkinite intrusives closely associated with these major crustal breaks, range in age from 800 to 670 Ma. Hence, these faults could well represent intracratonic lineaments of the Pan-African age.

The close spatial and temporal association of the sapphirine granulites to the deep crustal Kambam fault, which hosts carbonatite and syenite, strongly suggests that the sapphirine formation in the Kodaikanal ranges can be linked to the Pan-African tectonothermal event.

1. Muthuswamy, T. N. and Gnanasekaran, R., *J. Annamalai Univ.*, 1968, **23**, 183–196.
2. Grew, E. S., *J. Geol. Soc. India*, 1982, **23**, 469–505.
3. Mohan, A. and Windley, B. F., *J. Metamorphic Geol.*, 1993, **11**, 867–878.
4. Grew, E. S., *J. Geol. Soc. India*, 1984, **26**, 117–119.
5. Sivasubramanian, P., Natarajan, R. and Janardhan, A. S., *J. Geol. Soc. India*, 1991, **38**, 552–537.
6. Sivasubramanian, P., Natarajan, R. and Janardhan, A. S., *J. Geol. Soc. India*, 1992, **40**, 287–290.
7. Mohan, A., Prakash, D. and Motoyoshi, Y., *J. SE Asian Earth Sci.*, 1996, **14**, 221–243.
8. Subba Rao, D. V., Nirmal Charan, S. and Moeen, S., *J. Geol. Soc. India*, 1997, **49**, 7–12.
9. Ellis, D. J., *Contrib. Mineral. Petrol.*, 1980, **74**, 201–210.
10. Motoyoshi, Y. and Hensen, B., *Eur. J. Mineral*, 1989, **1**, 467–471.
11. Vielzeuf, D., *Contrib. Mineral. Petrol.*, 1983, **82**, 301–311.
12. Aranovich, L. Ya, Lavrent'eva, I. V. and Kosyakeva, M. A., *Geokhimiya*, 1988, N5, pp. 668–676.
13. Sengupta, P., Dasgupta, S., Bhattacharya, P. K. and Mukherjee, M., *J. Metamorphic Geol.*, 1990, **8**, 191–197.
14. Berman, R. G., *Can. Min.*, 1991, **29**, 833–855.
15. Jayananda, M., Janardhan, A. S., Sivasubramanian, P. and Peucat, J. J., *J. Geol. Soc. India*, 1995, **34**, 373–390.
16. Unnikrishnan-Warrier, C., Santosh, M. and Yoshida, *Geol. Mag.*, 1995, **132**, 253–260.
17. Anilkumar and Gopalan, K., *Curr. Sci.*, 1991, **60**, 653–655.
18. Odom, L. A., India, Rept UN Case 81-100084, 1982, pp. 1–9.
19. Rogers, J. J. W., Miller, J. S. and Clements, A. S., *Mem. Geol. Soc. India*, 1995, **34**, 11–23.
20. Grew, E. S. and Manton, W. I., *Precam. Res.*, 1986, **33**, 123–127.
21. Shaw, R. K., Arima, M. and Kagami, H., Abst. International workshop on the Proterozoic continental crust of southern India, Center for Earth Science Studies, Trivandrum (eds Santosh, M. and Yoshida, M.), 1966, pp. 123.
22. Grady, J. C., *J. Geol. Soc. India*, 1971, **12**, 56–62.

ACKNOWLEDGEMENTS. We thank Dr Steele of Chicago University, for the probe data. Prof. S. Sathyanarayan, Chairman, Dept of Geology is thanked for the facilities. Anto thanks UGC, New Delhi for financial support. A.S.J. acknowledges the IFCPAR programme under which the garnet ages were obtained. P.S. thanks the DST, New Delhi for financial assistance under the Young Scientists Programme.

Received 12 May 1997; revised accepted 25 August 1997

On the seismic vulnerability of Jabalpur region: Evidence from deep seismic imaging

P. R. Reddy, Kalachand Sain and A. S. N. Murty

National Geophysical Research Institute, Hyderabad 500 007, India

In light of our limitations in 'short-term earthquake prediction', detailed structural results from seismic studies could act as parametric inputs, in our pursuit for better understanding the seismicity of a region. A synthesis of seismic refraction/wide-angle reflection results of Hirapur–Mandla profile with other geological and geophysical signatures in central India, occurrence of seismic activity indicate presence of neotectonic activity. This assumes significance in light of the recent earthquake in Jabalpur region. Intense fracturing associated with the boundary fault near Jabalpur might have been responsible for the release of stress accumulated due to continuous northward movement of the Indian plate. It is suggested that detailed seismic surveillance is undertaken in and around the Narmada–Son lineament to more specifically pinpoint seismic vulnerability of the region.

THE controlled source seismic experiment is a powerful tool to image the crustal structure (faults/fracture zones)