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Orthopyroxene – Cordierite ± Sapphirine Symplectite Replacing Garnet: Diagnostic Evidence for Isothermal Decompression (ITD) in the Usilampatti, South India

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Abstract: **The Sapphirine granulites of the Usilampatti display evidence of metamorphic reactions involved in the formation of diverse mineral assemblages recognized in different types of reaction textures, symplectites and coronas. The analysis of symplectitic development is best studied through a combination of the maximum rate of energy dissipation and non-equilibrium thermodynamics. However, symplectite growth in rocks is mainly governed by any change in physical and/or chemical parameters. The evidence of melting and decompression reactions is seen in the petrographic studies of the symplectitic domains deciphering garnet, orthopyroxene and sillimanite resorption in various reaction textures and the development of orthopyroxene-cordierite as well as sapphirine-cordierite-orthopyroxene symplectites characterised by the retrograde cooling stage of metamorphism. The P-T conditions obtained from the symplectite compositions of sapphirine granulites suggest such reaction was effectuated by a decrease in pressure resulting in decompression of the order of 6 Kbar and a non-significant temperature drop indicating nearly isothermal decompression.**

Index Terms: **Southern Granulite Terrane, Madurai Block, symplectite, Granulites, winTWQ.**

I. INTRODUCTION

The Southern Granulite Terrane (SGT) forms a collage of several crustal blocks separated by extensive Proterozoic shear zones. The Madurai Block lies between the Palghat-Cauvery and the Achankovil shear zones (Prakash et al., 2010, 2018). Granulites are the high-grade metamorphic rocks that originate in the lower to mid-continental crust (John et al., 2005). Prakash and Arima, (2003) reported Sapphirine granulites that occur as layers between charnockites and recently, Clark et al. (2015) have published a note on the migmatites from Usilampatti.

The Madurai Block (MB) covers the largest area of the Southern Granulite Terrane (SGT) and is also related to ultrahigh-temperature (UHT) metamorphism (Prakash et al., 2010; Kooijman et al., 2011; Teale et al., 2011 and Tewari et al., 2017). The dominant magmatic lithologies in the Madurai Block are hornblende biotite (TTG) gneisses, charnockites and their intermediate enderbitic rocks, diorites, minor gabbros (including mafic granulites), pink and gray granitoids, pinkish and grayish granites and pegmatites. The metasedimentary units are represented by garnet-biotite gneiss, garnet-biotite-sillimanite gneiss, quartzites, and metacarbonates.

Sapphirine granulites are renowned from several terranes all over the world. In India, such rocks are known from the Madurai block (Kelsey and Hand, 2015 and references therein), the Palghat Cauvery tectonic zone (Kelsey et al., 2006), the Eastern Ghats Mobile Belt (Mukhopadhyay and Basak, 2009 and references therein), western India (Srikarni et al., 2004) and northeastern India (Lal et al., 1978).

The variety of reaction textures and mineral assemblages in the rocks of this area offer a wide spectrum of P-T sensors that provide a complete picture of physical conditions of metamorphism. In this way the present area allows an excellent opportunity to investigate the metamorphic evolution of a portion of granulite facies terrane, which is vital to the understanding of the evolution of the lower continental crust.

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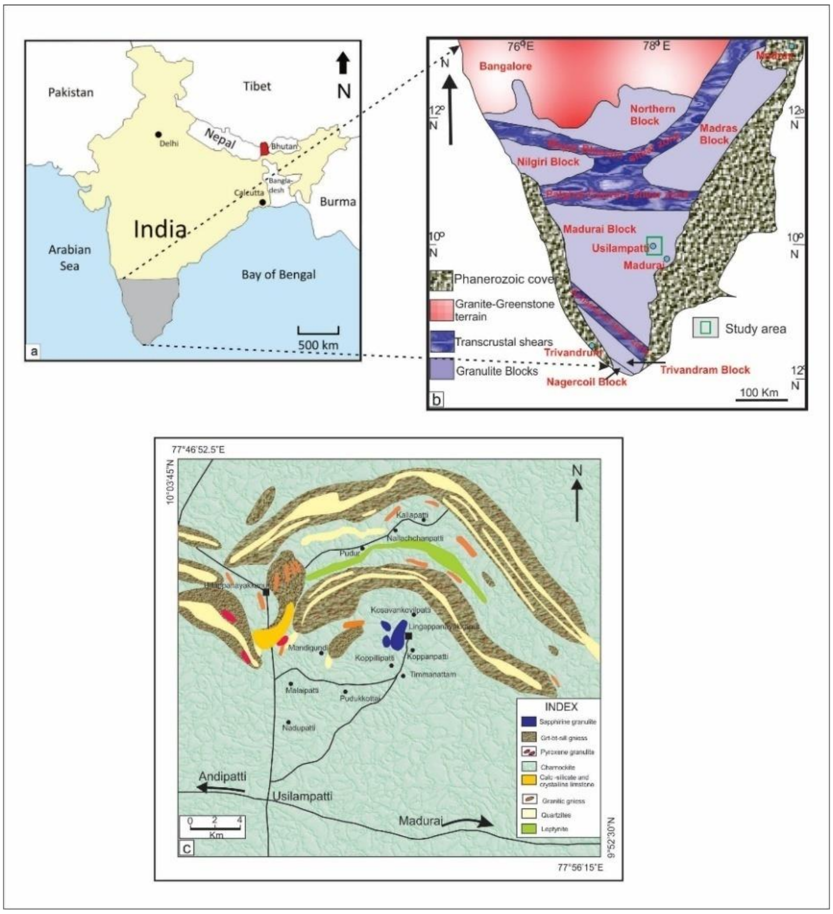

Fig. 1: (a) Reference map of India; (b) map of south India showing different granulite blocks and major Proterozoic shear zones; (c) geological map of the area around Usilampatti.

The main plan of this work is to describe the important textures encountered in the sapphirine granulites of the Usilampatti which when correlated would be helpful in the estimation of retrograde P-T trajectory in several other granulitic terranes.

II. GEOLOGICAL SETTING

Usilampatti is situated about 35 km northwest of the Madurai district, Tamil Nadu constitutes a part of high-grade granulite facies rocks of Southern Granulite terrane. The high-grade terrane of southern India is dissected by several major shear zones into several crustal blocks (Fig. 1b). The marked contrasts in lithology, structure and metamorphic history between adjacent crustal domains suggest that this complex high-grade terrane represents a tectonic collage of individual terranes that accreted during early- to late-Proterozoic tectonothermal events (Buhl, 1987; Peucat et al., 1989, 1992; Raith et al., 1990; Kohler et al., 1993; Choudury et al., 1993). Usilampatti offers nearly all the important high-grade metamorphic features, with excellent outcrops, and good logistical support.

The investigated area comprises a variety of granulitic rocks having diverse mineral assemblages. The main lithotypes of the area include charnockite, mafic granulites, garnet-cordierite-sillimanite gneisses, leptynites, sapphirine granulites and quartzites (Fig. 1c). Almost 10 km NE of Usilampatti, sapphirine granulite is exposed in an abandoned pit. Blue granular aggregates of cordierite and coarse biotite flakes along with brownish coarse-grained garnet are visible in the outcrop of sapphirine granulite.

III. TEXTURAL RELATIONSHIP

The Usilampatti granulites display various disequilibrium reaction textures, including coronas, as well as symplectites or resorption textures. The xenoblasts of garnet almost enclosed the fine symplectitic intergrowths of cordierite-sapphirine-orthopyroxene (Fig. 2a; garnet is almost consumed in this domain), which may be attributed to the reaction:

Garnet = Cordierite + Sapphirine + Orthopyroxene – (1)

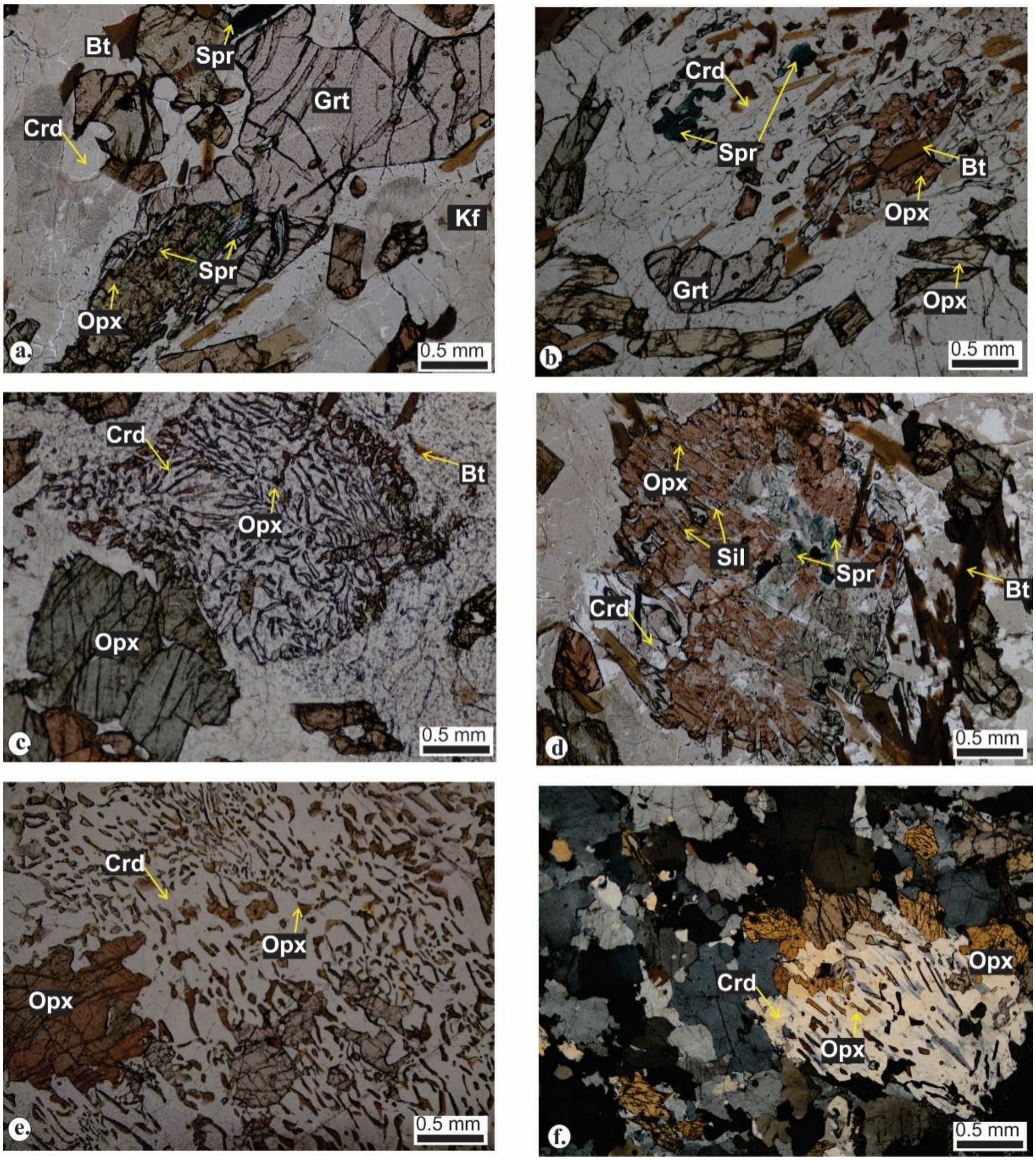

Fig. 2: Photomicrographs illustrating textural relations in sapphirine granulites from Usilampatti. a. Intergrowth of orthopyroxene-sapphirine symplectites replacing garnet (in XL); b. Relict grains of garnet surrounded by symplectite of orthopyroxene-cordierite and flakes of garnet also present (in XL); c. symplectitic intergrowth of orthopyroxene-cordierite that developed through the reaction Grt+Qtz = Opx+Crd (in XL); d. Orthopyroxene megacryst enclosing a symplectite of orthopyroxene+sapphirine+cordierite with laths grains of sillimanite (in XL); e. Symplectites of orthopyroxene-cordierite; Coarse grains of earlier generation orthopyroxene are also present (in XL); f. beautiful Symplectite of orthopyroxene and cordierite (in PL).

Similar textural breakdown features indicative of decompression have also been reported by Droop and Bucher-Nurminen (1984); Harley et al. (1990); Mohan et al. (1996); Mouri et al. (1996); Raith et al. (1997); Moraes et al. (2002). Subsequently, a sequence of symplectite assemblages orthopyroxene-cordierite, orthopyroxene- cordierite-sapphirine developed at the expense of garnet. Relict grains of garnets are surrounded by spectacular radial symplectite of orthopyroxene. No preferred orientation of cordierite (Fig. 2b) in the silica-saturated domain and may be explained by a continuous Fe-Mg exchange reaction:

Garnet + Quartz = Orthopyroxene + Cordierite – (2)

Prakash (1999); Osanai et al. (2001); Prakash and Arima (2003) have also reported similar textural breakdown of garnet in producing orthopyroxene-cordierite symplectites from pelitic granulites.

Development of cordierite-orthopyroxene symplectites (Fig.2 c, e, and f) makes up the textural evidence for the reaction (2) which is characteristic of isothermal decompression (Hensen and Green, 1972; Harley, 1989). Reaction (2) has been experimentally investigated by Richardson (1968) and Holdaway and Lee (1977) in the FASH system.

Table I: Representative microprobe analyses (oxide wt%) of Sapphirine Granulite (Sample-U1412)

	Grt	Grt	Opx	Opx	Spr	Spr	Crd	Crd
	R	C	S	S	S	S	S	S
Oxide Wt%								
SiO_2	39.14	38.38	48.47	48.82	13.23	13.03	48.97	48.00
TiO_2	0.04	0.00	0.06	0.19	0.01	0.00	0.00	0.00
Al_2O_3	21.72	22.59	9.28	9.42	61.37	60.56	32.72	33.11
Cr_2O_3	0.07	0.00	0.15	0.00	0.02	0.07	0.00	0.00
FeO	28.59	26.44	18.20	16.37	10.67	9.51	4.54	4.06
MnO	0.49	0.57	0.04	0.07	0.09	0.00	0.00	0.00
MgO	8.98	10.94	23.67	24.83	14.79	16.62	11.32	11.12
CaO	0.59	0.74	0.03	0.00	0.01	0.00	0.00	0.00
Na_2O	0.00	0.00	0.03	0.01	0.04	0.02	0.09	0.07
K_2O	0.00	0.00	0.07	0.00	0.00	0.00	0.04	0.05
Total	**99.62**	**99.67**	**100.00**	**99.71**	**100.34**	**99.80**	**97.67**	**96.40**
O.B.	12.00	12.00	4.00	4.00	10.00	10.00	8.00	8.00
Si	3.03	2.94	1.83	1.77	0.98	0.79	4.99	4.95
Al^{IV}	0.00	0.06	0.17	0.23	2.02	2.21	3.93	4.02
Al^{VI}	1.98	1.99	0.10	0.17	2.03	2.09	0.39	0.35
Ti	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.00	1.68	0.00	0.00	0.00	0.12	0.00	0.00
Fe^{2+}	1.85	0.04	0.68	0.50	0.44	0.35	0.00	0.00
Mn	0.03	0.06	0.01	0.00	0.00	0.00	0.00	0.00
Mg	0.05	1.25	1.24	1.34	1.53	1.49	1.72	1.71
Ca	1.04	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X_{Mg}	0.36	0.56	0.65	0.73	0.78	0.76	0.85	0.84

* Total iron asFeO

$X_{Mg}=Mg/(Mg+Fe^{2+})$

C=Core,R=Rim,S=Symplectie

Texturally, prismatic orthopyroxene is intermixed with sapphirine and while the latter engulfs sillimanite, the cordierite form rim around the orthopyroxene (Fig. 2d). These textural features favour the sapphirine forming reaction:

Qrthopyroxene + Sillimanite = Sapphirine + Cordierite – (3)

This reaction proceeds at the expense of Opx and Sill and has also been documented by Schreyer (1970), Droop and Bucher-Nurminen (1984), Bertrand et al. (1992), Mouri et al. (1996), Kriegsman and Schumacher (1999) and Bhattacharya and Kar (2002).

IV. MINERALOGY

The experimental work was carried out on the Electron Probe Micro Analyzer (EPMA) CAMECA SXFive instrument at DST-SERB National Facility, Department of Geology (Center of Advanced Study), Institute of Science, Banaras Hindu University. The CAMECA SXFive instrument was operated by SXFive Software at a voltage of 15 kV and current 10 nA with a LaB6 source in the electron gun for the generation of the electron beam. The representative microprobe analyses of various minerals are listed in Table I. Mineral abbreviations are followed after Kretz (1983).

Garnet constitutes the main mineral group in the metamorphic rocks which is important to interpret the genesis of the metamorphic rocks. Garnet porphyroblasts are intermediate pyrope–almandine solid solutions with minor spessartine and grossular. It is found as coarse-grained xenoblastic crystals. Garnet porphyroblasts contain inclusions of orthopyroxene, biotite and sapphirine. Garnet also shows textural evidence of breakdown to cordierite, sapphirine, orthopyroxene.

Orthopyroxene has high alumina (up to 9.42 wt%Al_2O_3). Orthopyroxene is an important component of the sapphirine granulite. The low mobility of Al may also be responsible for the high $A1_2O_3$ content in symplectites closely associated with coarse orthopyroxene. Besides coarse prisms, orthopyroxene also occurs as fine to medium-grained, xenoblastic crystals and as symplectitic intergrowths which belong to a later generation.

Cordierite is systematically richer in magnesium than coexisting phases. Occurs as anhedral grains of variable sizes. It is seen as colourless granoblastic polygonal grains, generally forming the matrix of a symplectitic intergrowth with quartz and orthopyroxene. Large cordierite grains are poikiloblastic and show lamellar and cyclic twinning. Cordierite with distinct pleochroic haloes around inclusions of zircon. The anhydrous sum of oxides in cordierite is less than 100%.

Sapphirine from study area mainly consists of MgO, Al_2O_3, SiO_2, and FeO and highly aluminous (up to 61.37 wt% Al_2O_3). The strongly pleochroic nature of sapphirine may be due to a high Fe content. Sapphirine forms symplectite with cordierite and orthopyroxene.

V. P – T CONDITION

The P-T evolution of the sapphirine granulite has been constrained through the internally consistent winTWQ

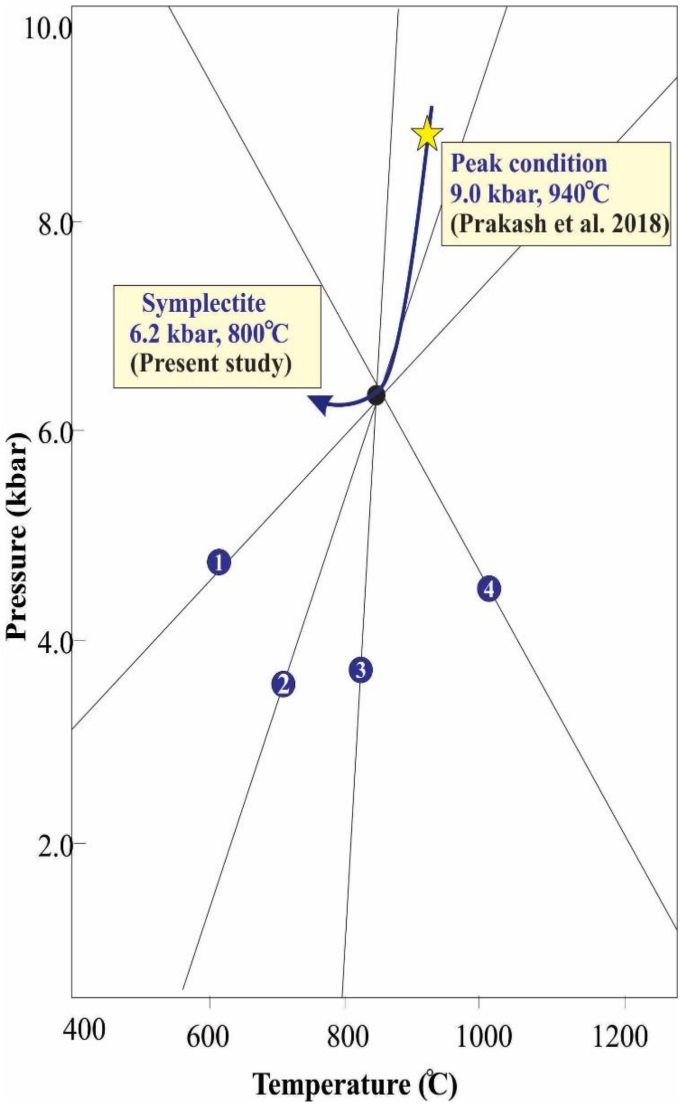

Fig. 3 P-T condition at decompression stage as obtained by application of the winTWQ programme (version 2.32).

programme version 2.32 (Berman, 1991; updated 1997). In the winTWQ programme, P and T were determined from the intersection of different reactions in P-T space, using the thermodynamic datasets of Berman (1988), Berman et al. (1995) and Berman and Aranovich (1996) for end-member phases. The end-member phases used in the winTWQ calculation were enstatite, ferrosilite, almandine, pyrope, cordierite, Fe-cordierite and β-quartz. Possible equilibria can be written for the selected endmember phases (Table II).

Symplectite compositions for the sample give an intersection using these equilibria suggesting 800°C and 6.2 kbar (Fig. 3) for symplectite which suggests isothermal decompression in the area. Isothermal decompression is also evident from symplectites of orthopyroxene-cordierite and orthopyroxene-sapphirine-cordierite.

Table II: Simultaneous calculation of Pressure-Temperature condition of Sapphirine Granulite (sample no. U1412, Symplectite) by winTWQ programme and assemblage used Grt-Opx-Crd-Qtz. P-T condition obtained by specific equilibria is 6.2 kbar and 800°C.

S. No.	Equilibria Plotted	S (J/M)	V (J/BAR)
1.	4Alm + 2 Py + 9 bQz = 12 Fsl + 3 Cd	105.82	19.44
2.	fCd + 4 Fsl = 3 bQz + 2 Alm	-44.45	-6.74
3.	3 fCd + 2 Py = 3 Cd + 2 Alm	-27.53	-.771
4.	2 fCd + 2 Py + 3 bQz = 4 Fsl + 3 Cd	16.92	5.96

DISCUSSION AND CONCLUSION

Usilampatti granulites thermal peak condition suggests they are formed under the UHT regime (Prakash et al. 2018). These granulite rocks preserve a record of their P-T evolution because of the development of spectacular reaction textures, strong refractory nature of minerals and varied mineralogy. The evolutionary stages from reaction textures combined with geothermobarometry suggest a clockwise P-T trajectory with nearly isothermal decompression (ITD path). Granulites occurring in the study area display various promising disequilibrium reaction textures that represent distinct segments of the P-T path during the granulite facies metamorphism. Such a textural study is important because the granulites of south Indian shield are generally thought to be polymetamorphic having multi-tiered textural resetting. Existence of garnet and cordierite in granulites is particularly helpful in determining the metamorphic evolutionary history and uplift tectonics, as product cordierite reflects the inversion of higher-pressure assemblages to lower pressure ones along an isothermal decompression path. Resorption of garnet through a sequence of reaction textures and the development of spectacular symplectites along with cordierite forming reactions are diagnostic of decompressional regime. The P-T conditions obtained for sapphirine granulite symplectite composition shows 800°C and 6.2 kbar which suggests the isothermal decompression. The present study suggests that isothermal decompression is also evident from symplectites of several minerals like orthopyroxene-cordierite and orthopyroxene–sapphirine-cordierite. The decompressional P-T trajectory may be recognized to a tectonic setting dominated by exhumation after crustal thickening. Isothermal decompression is suggestive of collisional orogeny leading to overthickened crust abiding which pressure-induced temperature increase and subsequent (Heat Producing Elements) HPE enrichment forming Large Hot Orogen (LHO) could be served as the major cause of HT/UHT metamorphism in Madurai block. Another not with standing question here arises is that how did the symplectites form? In essence, symplectites usually are thought to be an intergrowth of two or more minerals on the advancing front. However, intergrowth of minerals in one another is just not confined to thermodynamic factors but also the geochemical factors like ion/element mobility within the layers play a significant role. The geochemical finding shows Al-rich symplectititc domains from which this may be manifested that Al enrichment within the advancing system during decompression could be attributed either to Al ingression from some external source or the involved mineral(s) themselves are acting as an alumina feeder. No evidence of external alumina enrichment, presence of Al-rich minerals like Opx and Sillimanite with no or minimal Al and Si mobility out of the system altogether relates to a plausible explanation to why and how the vermicules of various assemblages could have formed within these rocks.

The study concludes that the preserved signatures of the different stages of metamorphic crystallization in the form of symplectites and other reaction textures can be highly rewarding in unravelling the tectonic and crustal evolution in the Madurai Block and hence the SGT.

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