Volume 65, Issue 5, 2021
Journal of Scientific Research
of
The Banaras Hindu University

Ultra-High Temperature metamorphism of Southern Granulite Terrain, India: A Review

C. K. Singh and D. Prakash
Centre of Advanced Study in Geology,
Banaras Hindu University
Varanasi-221005
e-mail: chandrakantbhu@gmail.com, dprakashbhu@gmail.com

Abstract: Ultra-High Temperature (UHT) metamorphism provide an opportunityto access the mid/lower continental crust as regard to crustal evolution. In India it has been reported from several localities of Southern Indian Terrain(SGT). The Southern Granulite Terrain, especially Madurai Block has been significantly investigated and considered as a natural laboratory for petrologists to solve the controversies of Precambrian crustal evolution. The Achankovil shear zones (ASZ) and the Palghat-Cauvery shear zones (PCSZ) bounds the limit of the Madurai Block from south and north respectively. Present work is an attempt to provide a comprehensive review of UHT terrains of SGT. The present work suggests that future detail petrological studies concurrence with metamorphic P-T path, psuedosection modeling along with dating of UHT terrains of Madurai Block may provide significant clues regarding crustal evolution of SGT.

Index Terms: **Sapphirine granulites, UHT metamorphism, Madurai Block, Southern Granulite Terrain**

I. INTRODUCTION

High-grade metamorphic rock Granulites evolved approximately in the lower/mid continental crust (Yadav et al., 2021a, b). The ultrahigh-temperature (UHT) regional metamorphism of crustal rocks usually subjected to temperature range of 900–1100 °Cwith moderate pressures of 7–13 kbar(Harley 1998; Prakash and Lal 2008).

Kodaikanal area comprised ofmajorupland granulite massifs in southern India is an integral part of Madurai Block. Mafic granulites, argillaceous - arenaceous - calcareous metasediments, anorthosites, charnockites and disconnected granite bodies are the principal lithology of this massif. The distinctivegarnet – sapphirine - cordierite assemblages more common in the central part of the upland massifs.

DOI: 10.37398/JSR.2021.650503

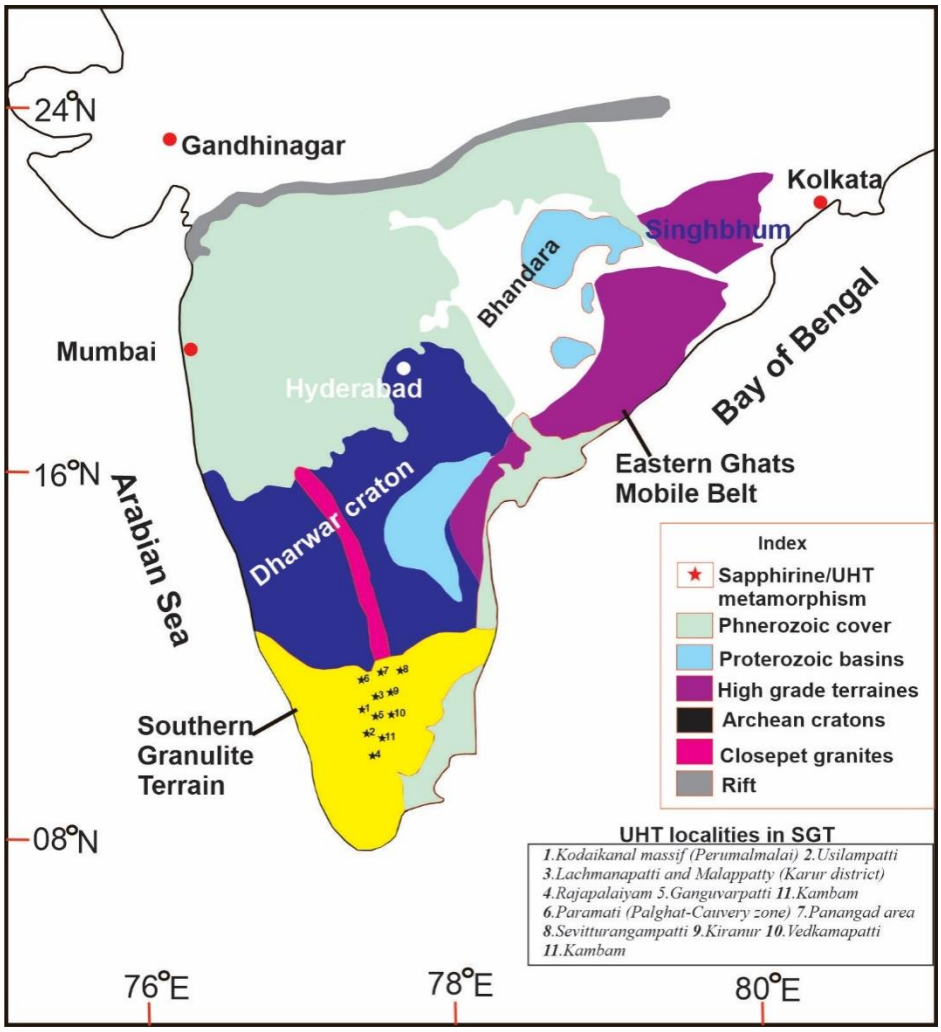

Fig. 1 Locations of the sapphirine/UHT metamorphism

On the other hand, metamorphosed pelitic rocks showing mineral assemblages of garnet - sillimanite - cordierite – spinel-sapphirine - orthopyroxene occur in adjacent areas(Prakash et al., 2006).In the Usilampatti, Andipatti, Ganguvarpatti etc. which are in fact low-lying areassillimanite - garnet bearing assemblages are characteristically common. Mafic granulites are generally interlayered with metasediments show presence of characteristic two-pyroxene (opx and cpx) assemblages (Prakash et al., 2007a,b).

Since last four decades the southern granulite terrain (SGT) has received considerable attention from petrologists especially working on crustal evolution controversies. It is worthwhile to mention here that sapphirine-bearing granulites is a strong evidence for UHT metamorphism. For interpreting pressure-temperature-time (P-T-t) path the sapphirine-bearing granulites serveas an irreplaceable tool because this refractory mineral holds the signatures of metamorphic history experienced throughout their evolution (Prakash et al. 2013, 2015, 2019,2021). Petrological investigations on the sapphirine-bearing granulites in Palni Hills of southern block of SGT from different localities located south of the PCSZ have provided signatures of UHT metamorphism(Tewari et al., 2018).The clockwise-iso-thermal decompression paths (CW-ITD)have been characteristically noticed. P-T paths arecharecterised by

multi-stage exhumation history (Prakash and Arima, 2003; Prakash et al., 2006;Tewari et al., 2018).

II. EXAMPLES OF UHT METAMORPHISM FROM SOUTHERN GRANULITE TERRAIN

A.Kodaikanal massif (Perumalmalai)

The extensive petrological studies of the garnet-bearing charnockites, sapphirine - bearing granulites, garnet – cordierite gneisses, charnockites, leptynites and migmatitic gneisses have been carried out by Mohan and Prakash 1996, Mohan et al. 1996 a, b; Prakash and Mohan 1999, Prakash 1999a, b; Sajeev et al. 2006, Tadokora et al. 2007.

In the Palni Hill ranges, prograde high pressure assemblage such asgarnet – plagioclase -biotite – orthopyroxene – kyanite –- quartz have been recorded by Raith et al. (1997). The signatures of decompression reactions and melting from Perumalmalai area have also been recorded by Prakash and Arima (2003). In the sapphirine-sillimanite associated granulites, biotite and sillimanite are separated by cordierite and sapphirine while the radiated replacement of garnet by biotite in a silica saturated domain which is mantled by plagioclase, provides the evidence for melt consuming reaction. In the Madurai Block near Kodaikanal the mafic granulites represent metamorphosed basalt showing REE fractionation and Fe-enrichment trend (Prakash and Thomas, 2005; Prakash, 2006).

B) Usilampatti

In Usilampatti the blue colouredpleochroic Sapphirine, occurs as spindle-shaped grains having main texture characterized by the cordierite + sapphirine symplectite and it is formed by orthopyroxene + sillimanite.

The cordierite-bearing rocks from Usilampatti have been computed for P-Tmaxas 6.5-7.5 kbar/ 750-800 °C whilesymplectite of spinel-cordierite yielding lower P-T as 600-670 °C and 5 kbar. Sapphirine-bearing granulites that occur as layers between charnockites (opx-kfs-bt-qtz) has also been recorded by Prakash and Arima(2003) whereas on the other hand sapphirine – bearing granulites contain needle shaped intergrowthof sillimanite with biotite. The coarse porphyroblasts of cordierite are associated with sapphirine as granular aggregates and show bluish-ink colour. Sapphirine bearing granulite records the highest P-T conditions (960°C and 9.2 kbar) from the Usilampatti area (Yadav et al. 2021b).

C) Lachmanapatti and Malappatty (Karur district)

Ackermand et al. in 1981 reported occurrenceof sapphirine granulites from Karur area. Intercalations of sapphirine in orthogneissesare common at Lachmanatti and Malappatty area within in the northern part of the Madurai Block (Tsunogae and Santosh, 2003). Needle-like intergrowth of sapphirine is common in these localities and occurs in symplectites of cordierite and corundum.Medium to fine-grained,euhedraland occasionally subhedral crystals of sapphirineare allied with corundum and cordierite in Lachmanpatti areahowever,in Malappatty area it shows the association with gedrite, plagioclase and corundum. In the northern Madurai Block sapphirine-corundum bearing granulites reported from above areashave preserved a significant testimonyof the nature of UHT metamorphism and exhumation record. The peak metamorphic conditions around 950–1000 °C with a pressure about 10 kbarhave beenestimated for the granulites of theSakkarakkottai area, Sengal area and Mettanganam areawhich suggest extreme UHT crustal metamorphism (Tsunogae and Santosh, 2003).In addition, metamorphic evolution of UHT the UHP mafic granulites ofKarurarea have also been discussed by Prakash et al. (2010).

D) Rajapalaiyam

Sriramguru et al. (2002) identified the localities of sapphirine-bearing granulites from the Rajapalaiyam area. It was the first report from Rajapaliyam area. The country rocks are igneous charnockites and pink granites in which sapphirine-bearing rocks are present as layered gneisses (Tateishi et al., 2004). Sapphirine shows varied associations such asgarnet enclosed fine-grained subhedralSapphirineallied with quartz, intergrowth of Sapphirine with Al-rich orthopyroxene, and in symplectitic intergrowth ofcordierite, orthopyroxene andsapphirine

surrounding the garnet. Sapphirine + quartz assemblage has been considered by these workers as key indicator of UHT metamorphic conditions.Tsunogae and Santosh (2006) reported UHT metamorphism and proposed counterclockwise P–T trajectory path for these sapphirine granulites. UHT metamorphism has also been reported by Braun et al. (2007) on the basisof sapphirine–quartz associationpresent in the garnet. Analyses of melt-producing and melt-consuming reactions yields a decompression P–T pathwhich is clockwise in manner in the P-T range of 8–11 kbar and 1000–1100 °C. Shan Shan Li et al. (2019) suggest that the sapphirine included in the garnetindicates temperature more than 1000 °C from the Rajapaliyam area.

E) Ganguvarpatti

Mohan and Windley (1993)suggested decompression during uplift history deduced from a sequence of reactions from the spectacular textural imprints and inferred a clockwise P-T path of exhumation of these granulites.Sajeev et al. (2001) have further modified the metamorphic history in Ganguvarpatti area.They reported Kornerupine and also recorded significant signatures of UHT metamorphism.The clockwise P-T path showing decompressional exhumation for sapphirine-bearing granulites have also been suggested by Sajeev et al. (2001).

F) Paramati (Palghat-Cauvery zone)

Paramati represents the northern limit of the PCSZ. Koshimoto et al. (2004) reported Mg-Al granulite rocks from Paramati having significant content ofcorundum and sapphirine.The shape of medium-grained crystals of sapphirine are mostly euhedral to subhedral.It is associated with spinel and sillimanite inclusions enclosed within plagioclase.Most of the time these are locally intergrown with corundum. Koshimoto et al. (2004) study infers that like central part of Madurai Block the sapphirine-corundum gneisses from Paramati experienced UHT peak metamorphism at T >900 °C (Fig.1).

I) Panangadarea

Collins et al. (2007) reported first time UHT granulites from Panangad area.Their finding is based on presence of prograde staurolite and sapphirine +cordierite + sapphirine corona from the above area. Here in this terrain cordierite bearing symplectites are inferred as indicator of near isothermal decompression.

II) Sevitturangampatti

The characteristic UHT assemblage such as garnet + sillimanite + sapphirine + cordierite ± spinel ± gedritehas been described from Sevitturangampatti by Shimpo et al. (2006). Garnet-corundum assemblage is indicator of Ultra-High Pressure (UHP) assemblage (Shimpo et al. (2006). But Kelsey et al., (2006) debated such an Ultra-high pressure condition as it would needexplanation of the stability ofgarnet+corundum±magnesianstaurolite assemblages at very high pressure. It is justified with the help of mineral equilibria through the simplified petrogenetic grid in MAS system (Shimpo et al., 2006) but still controversy regarding UHP assemblages exists (Fig.1).

G) Kiranur

Lal et al. (1984) reported Mg-Al granulite rocksin the form of enclaves within the gneisses from Kiranur. In the pseudomorphs aggregates of sillimanite enclosed bladed kyanite crystal are present here.In addition, coexistence of kyanite and staurolite are also common whileGedriteoccurred here as corroded blebs within orthopyroxene. These textural evidences from Kiranurconvincingly concludes that the prograde clockwise P-T path would have passed through kyanite = sillimanite equilibrium.

H) Vedkamapatti

Tiwari and Sarkar (2020) reported UHT metamorphism with the development of high X_{Mg}garnet (upto 0.69) + orthopyroxene (Al_2O_3upto 9.6 wt %)assemblage from the eastern Madurai domain.

In addition to above localities the granulites from Kambam area (Anto et al., 1997; Rai et al. 2021) also show evidences of UHT metamorphism in Madurai Block.

CONCLUSION

The authorsare associated with the study of crustal evolution of Madurai block and findings are being analysed to evaluate the tectono-metamorphic significance of sapphirine bearing granulites in the entire Madurai block. The above information may throw light on the crustal evolution of the UHT metamorphic rocks uplifted/exhumed from deep levels of the crust in Southern Granulite Terrain.

ACKNOWLEDGMENT

Authors are grateful to the DST- SERB New Delhi, India (Project No. P-07/704) for financial support for this work.The authors thank anonymous reviewer for suggesting significantimprovements to the manuscript.

REFERENCES

Ackermand, D., Lal, R. K., Raase, P. &Raith, M. (1981). Metamorphic conditions in the high-grade terrain of south India: Deduced from Sapphirine-bearing granulites from Kiranur, Karur (Tamil Nadu). RevistaBrasileira de Geociencias, 12, 284-291.

Anto, K.F., Janardhan, A.S. & Sivasubramanian, P. 91997). A new sapphirine occurrence from Kambam valley, Tamil Nadu and its possible relation to the Pan-African tectonothermal event. *Current Science*, 73, 792-796.

Braun, I., Cenki-Tok, B, Paquettec, J.L. & Tiepolo, M. (2007). Petrology and U–Th–Pb geochronology of the sapphirine-quartz-bearing metapelites from Rajapalayam, Madurai block, Southern India: evidence for polyphase Neoproterozoic high-grade metamorphism. *Chemical Geology*, 241, 129-147.

Collins, A. S., Clark, C., Sajeev, K., Santosh, M., Kelsey, D. E. & Hand, M. (2007).Passage through India : The Mozambique ocean suture, high pressure granulites and the Palghat-Cauvery Shear system. *Terra Nova*, 19,141-147.

Harley, S. L. (1998). On the occurrence and characterization of ultrahightemperature crustal metamorphism. In: Treloar, P.J., O'Brien, P.J. (Eds.), What Drives Metamorphism and Metamorphic Reactions?,*Geological Society of London*, 138. 81–107 (Special publication).

Kelsey, D. E., Clark, C., Hand, M. & Collins, A. S. (2006). Comment on "First report of garnet–corundum rocks from southern India: implications for prograde high-pressure (eclogite-facies?) metamorphism" by Shimpo et al. [Earth and Planetary Science Letter 242 (2006) 111–129]. *Earth and Planetary Science Letter*,249, pp.529–534.

Koshimoto, S., Tsunogae, T. & Santosh, M. (2004). Sapphirine and corundum bearing ultrahigh temperature rocks from the Palghat-Cauvery shear system, Southern India. *Journal of Mineralogical and Petrological Sciences*, 99, 298-310.

Lal, R. K., Ackermand, D., Raith, M., Raase, P. & Seifert, F. (1984). Sapphirine-bearing assemblages from Kiranur, southern India: a study of chemographic relationships in the Na_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O system. *NeuesJahrbuchfu¨rMineralogie, Abhandlungen* 150, 121–152.

Mohan, A. & Prakash, D. (1996). Textural relationship in Sapphirine-granulites from Kodaikanal and their implication. *Indian Mineralogist*, 30, 1-12.

Mohan, A., Prakash, D. &Motoyoshi, Y.(1996a). Decompressional P-T history in sapphirine-bearing granulites from Kodaikanal, Southern India. *Journal of Asian EarthScience*, 14, 231-243.

Mohan, A., Prakash, D. &Sachan, H. K. (1996b). Fluid inclusions in charnockites from Kodaikanal massif (South India) : P-T record and implications for crustal uplift history. *Mineralogy and Petrology*, 57, 167-184.

Mohan, A., Windley, B. F. (1993). Crustal trajectory of sapphirine bearing granulites from Ganguvarpatti, South India: evidence for an isothermal decompression path. *Journal of Metamorphic Geology*, 11, 867-878.

Prakash, D. & Mohan A. (1999). Carbonic rich fluid inclusions in granulites from Kodaikanal, South India.

"Charnockite and granulite facies rocks, Madras ,(Ed. Murthy and Ram Mohan, 361 - 370.

Prakash, D. (1999a). Petrology of the basic granulites from Kodaikanal, South India. *Gondwana Research*, 2,95-104.

Prakash, D. (1999b). Cordierite-bearing gneisses from Kodaikanal, South India: Textural relationship and P-T conditions. *Journal Geological Society of India*, 54, 347-358.

Prakash, D. &Arima, M. (2003). High-temperature dehydration melting and decompressive textures in Mg-Al granulites from the Palni hills, South India. *Polar Geosciences*, 16, 149-175.

Prakash D. & Thomas H. (2005).Geochemistry and Petrogenesis of the high gradeGranulites from Kodaikanl, South India**.**Felicitation volumes of Prof. R. S. Sharma, Topic:Granulite Facies Metamorphism and Crustal Evolution, 347-362.

Prakash, D., Arima, M. & Mohan, A. (2006). UHT metamorphism in the Palni Hills, South India: Insights from feldspar thermometry and phase equilibria. *International Geology Review*, 48, pp.6 19-638.

Prakash, D. (2006). Metamorphic reactions and P-T estimates of Ultra-high temperature mafic granulites from NE Madurai block, South India. *Indian Journal of Geochemistry*, 21, 49-70.

Prakash, D., Arima, M. & Mohan, A. (2007a). Ultrahigh-temperature mafic granulites fromPanrimalai, South India: Constraints from phase equilibria and thermobarometery. *Journal ofAsian Earth Science*,69, 285-290.

Prakash, D., Arima, M. &Mohan, A. (2007b). Colour-coded compositional mapping of orthopyroxene-plagioclase symplectites in mafic granulites from Panrimalai, South India. *Journal Geological Society of India*, 69, 285-295.

Prakash, D. & Lal, S.N. (2008). UHT metamorphism and its significance in Madurai block, South India. *Geolgical Survey of India Special Publications* 91, 28-42.

Prakash, D., Prakash, S.&Sachan, H. K. (2010). Petrological Evolution of the High-Pressure and Ultrahigh-Temperature mafic granulites from Karur, Southern India: Evidence for decompressive and cooling retrograde trajectories. Mineralogy and Petrology, 100, 35–53.

Prakash, D., Singh,P. C.&Hokada, T.(2013). A new occurrence of sapphirine-spinel-corundum-bearing granulite from NE of Jagtiyal, Eastern Dharwar Craton, Andhra Pradesh. *Journal of the Geological Society of India*, 82, 5–8.

Prakash, D., Deepak, Singh, P. C.,Singh,C. K., Tewari,S., Arima,M. &Frimmel,H. E. (2015). Reaction Textures and Metamorphic evolution of sapphirine-spinel bearing and associated granulites from DiguvaSonaba, Eastern Ghats Mobile belt, India. *Geological Magazine*, 152(2), 316–340.

Prakash, D., Vishal,B.,Naik, A. S., Yadav, R., Rai, S. K., Tewari, S., Yadav, M. K., Tiwari,S., Das, S. &Pattnaik, C. (2019). New Occurrence of Sapphirine-spinel-bearing Granulite from NW of Chilka Lake, Eastern Ghats Belt, Odisha. The *Journal Geological Society of India*, 93, 153–156.

Prakash, D., Kumar, M., Rai, S. K., Singh, C. K., Singh, S., Yadav, R., Jaiswal, S., Srivastava, V., Yadav, M. K., Bhattacharjee, S., & Singh, Pradip K.(2021). Metamorphic P-T evolution of Hercynite-quartz-bearing granulites from the Diwani Hill, North East Gujarat (NW India). *Precambrian Research*, 352, 1-19.

Rai, S, K., Prakash, D., Yadav, R., Jaiswal, S., Kumar, R. S., & Singh, C. K. (20210. New Finding of Silica-deficient Sapphirine-bearing Granulites from NNE of Suranganar Village, Southern Madurai Block, India. *Journal Geological society of India*, 97, 255-260.

Raith, M., Karmakar, S., &Brown, M. (1997). Ultrahigh-temperature metamorphism and multi-stage decompressional evolution of sapphirine granulites from the Palni hill ranges, Southern India. *Journal of Metamorphic Geology*, 15, 379-399.

Sajeev, K., Osanai, Y.&Santosh, M. (2001). Ultrahigh-temperature stability of sapphirine and kornerupine in Ganguvarpatti granulite, Madurai Block, southern India. *Gondwana Res*earch. 4, 762-766.

Sajeev, K., Santosh, M. &Kim, H.S. (2006). Partial melting and P–T evolution of the Kodaikanal Metapelite Belt, southern India. *Lithos*, 92, 465-483

Sriramguru, K., Janardhan, A.S., Basava, S. &Basavalingu, B. (2002).Prismatine and sapphirine bearing assemblages from Rajapalaiyam area, Tamil Nadu: origin and metamorphic history. *Journal Geological Society of India*, 59, 103–112.

Tewari, S., Prakash, D., Yadav, M. K. &Yadav, R. (2018). Petrology and isotopic evolution of granulites from central Madurai Block (southern India): reference to Ediacaran crustal evolution. *International Geology Review*, 60, 1791–1815.

Shan-Shan Li,Palin Richard M., Santosh, M.,Shaji, E.& Tsunogae, T. (2019). Extreme thermal metamorphism associated with Gondwana assembly: Evidence from sapphirine-bearing granulites of Rajapalayam, southern India. *Geological Society of America Bulletin*,132 (5-6), 1013–1030

Shimpo, M., Tsunogae, T. & Santosh, M. (2006). First report of garnetcorundumrocks from southern India: implications for progradehigh-pressure (eclogite-facies?) metamorphism. *Earth and Planetary Science Letter*, 242, 111–129.

Tadokoro, H., Tsunogae, T., Santosh, M. & Yoshimura, Y. (2007). First report of spinel+quartz assemblage from Kodaikanal in the Madurai Block, southern India: implications for ultrahigh-temperature metamorphism.*Inter-national Geology Review*, 49, 1050-1068.

Tateishi, K., Tsunogae, T., Santosh,M. &Janardhan, A.S. (2004). First report of Sapphirine + Quartz assemblage from southern India: Implications for ultrahigh - temperature metamorphism. *Gondwana Research*, 7, 899-912.

Tiwari, A. K. & Sarkar, T. (2020). P-T-t evolution of sapphirine-bearing semipelitic granulites from Vadkampatti in Eastern Madurai Domain, southern India: Insights from petrography, pseudosection modellingandin-situ monazite geochronology. *Precambrian Research*. 348, 105866.

Tsunogae, T. & Santosh, M. (2003). Sapphirine and corundum-bearing granulites from Karur, Madurai block, Southern India. *Gondawana Research*, 6, 925-930.

Tsunogae, T. & Santosh, M. (2006). Spinel-sapphirine-quartz bearing composite inclusion within garnet from an ultrahigh-temperature pelitic granulite: implications for metamorphic history and P-T path. *Lithos*, 92, 524-536.

Yadav, R. Prakash, D. & Rai, S. K. (2021a). Orthopyroxene – Cordierite ±Sapphirine symplectite replacing Garnet: Diagnostic evidence for Isothermal Decompression (ITD) in the Usilampatti, South India. *Journal of Scientific Research*,65, 51-58.

Yadav, R., Prakash, D., Rai, S. K., Yadav, M. K.,Jaiswal, S., Singh, S., Singh, P. K., Kumar, M.& Singh, C. K. (2021). Ultrahigh-temperature decompression of sapphirine-granulites from the southern Madurai block (South India): Insights from geothermobarometry, pseudosection modelling and U-Pb geochronology. *Journal of Asian Earth Science*, 218, 104861.

***