MINERALOGICAL MAGAZINE, MARCH 1970, VOL. 37, NO. 289

Paragenesis of staurolite in pelitic schists of Kishangarh, District Ajmer, India

R. K. LAL and R. S. SHUKLA
Department of Geology, Banaras Hindu University, Varanasi, India

SUMMARY. The staurolite-bearing schists of the area were metamorphosed in the staurolite–kyanite zone of the amphibolite facies. The various assemblages of the pelitic schists are represented in the AKF and Thompson's AFM diagrams. Within the *PT* conditions of stability of staurolite, this mineral develops in pelitic schists that have a high Al_2O_3 (excess)/(K_2O+FeO+MgO) ratio so that the plots of analyses lie above the muscovite–garnet join in the AKF diagram. The three-phase field of staurolite–kyanite–biotite in the AFM diagram migrates towards the lower FeO/MgO side with increasing oxidation ratio and thus staurolite-bearing rocks are not necessarily restricted to pelitic schists with high FeO/MgO ratio as is commonly believed. On the other hand, the three-phase field shifts towards the higher FeO/MgO side with increasing grade of metamorphism assuming oxidation ratio and pressure to be constant, thus reducing the composition field of staurolite schists in the AFM diagram.

PELITIC rocks containing staurolite commonly occur in medium- to high-pressure regional metamorphism in staurolite–kyanite and sillimanite–muscovite zones of the amphibolite facies of Turner (1968), where staurolite is associated with almandine, muscovite, kyanite (or sillimanite), and quartz. Staurolite-bearing rocks are not always encountered even though the *PT* conditions lie within the stability field of staurolite, which led several petrologists to suggest that the bulk chemical composition plays an important role in the formation of staurolite in pelitic schists. Turner and Verhoogen (1960), Winkler (1965), and Turner (1968) are of the opinion that staurolite-bearing rocks are formed in pelitic schists that are rich in Al_2O_3 and FeO and poor in K_2O. On the other hand, many petrologists would attribute the rarer development of staurolite as compared with garnet, biotite, kyanite, and sillimanite to a more restricted temperature-pressure range (Deer, Howie, and Zussman, 1962) or a limited range of oxygen fugacity (Ganguli, 1968).

Phase relations of various staurolite-bearing assemblages of pelitic schists present an interesting problem, for these rocks often contain a greater number of phases than is expected from the mineralogical phase rule, e.g. five phases, a staurolite, kyanite, biotite, muscovite, and garnet assemblage, in the four-component system Al_2O_3, FeO, MgO, and K_2O. Besides this, the FeO/MgO ratio of garnet and biotite coexisting with staurolite is sensitive to the variation in oxidation ratio (Chinner, 1960; Hounslow and Moore, 1967) and increasing grade of metamorphism (Chinner, 1965), which further complicates the phase relations.

An attempt has been made in this paper to discuss the problems mentioned above in the light of mineralogical and chemical data from Kishangarh and other areas.

Geological setting. The area described in this paper falls in the Survey of India topological sheet no. 45 J/14 and extends from 26° 34′ to 26° 37′ N. and 74° 50′ to 74° 54′ E. The rocks of the area belong to the Precambrian age. Niyogi (1965) has described the stratigraphy and structure of the area. The staurolite-bearing rocks represent a distinct lithological unit in the area and are associated with micaceous quartzite, calcsilicates, graphitic schists with marble, amphibolites, etc. The rocks strike in NE.–SW. direction and are folded into isoclinal synclines and anticlines plunging at one or both ends.

Petrography of the staurolite schists. The rocks are dark coloured and coarse-grained with a distinct schistosity. Crystals of staurolite are easily distinguishable and their size varies from less than 1 cm to more than 4 cm in length. Garnet occurs as small crystals and because of its sporadic occurrence is not easily visible megascopically. Large sky blue blades of kyanite are conspicuous in the kyanite–staurolite schists.

Biotite is pleochroic with α yellowish-green, β and γ deep greenish-brown, and contains strongly pleochroic halos about inclusions of zircon. It is frequently intergrown with associated muscovite and shows retrogression to chlorite and iron oxide. Staurolite is porphyroblastic and poikiloblastic, containing numerous inclusions of quartz, which are sometimes rolled. Besides quartz, it also contains inclusions of biotite, opaque 'ores', garnet, etc. It shows alteration to sericite and chlorite along the grain boundaries. In a few thin sections, it is more or less completely altered to a 'shimmer aggregate' of sericite and chlorite, which forms a pseudomorph after staurolite. Garnet occurs as small idioblastic grains containing few inclusions of quartz and rarely exceeds 3 %. Kyanite occurs in coarse prisms showing (010) and (100) cleavages, sometimes surrounded by a rim of muscovite. Plagioclase (An_{22} to An_{30}) occurs along with quartz in the leucocratic bands and commonly contains numerous inclusions of quartz and opaques. Accessories include sphene, apatite, tourmaline, magnetite, ilmenite, hematite, zircon, etc.

In the pelitic mineral assemblages of the area, quartz and plagioclase may be accompanied by: muscovite alone; muscovite and biotite; muscovite and garnet; staurolite, muscovite, and biotite; staurolite, muscovite, biotite, and garnet; or staurolite, muscovite, biotite, and kyanite. The widespread occurrence of staurolite with or without kyanite, and the presence of plagioclase (with An 22 to 30) suggest that the rocks of the area studied belong to the staurolite–kyanite zone of Turner (1968).

Paragenesis of staurolite in pelitic schists. Chemical analyses of the rocks and minerals (tables I and II) were performed by methods mostly based on Shapiro and Brannock (1956, 1962) and Hounslow and Moore (1966). The analyses are plotted on the AKF and Thompson's AFM diagrams (figs. 1 and 2).

In the AKF diagram (fig. 1) the staurolite-bearing rocks of Kishangarh and other areas lie above the muscovite–garnet join and have a higher Al_2O_3 (excess)/(K_2O+FeO+MgO) ratio as compared to common argillaceous rocks. Pelitic rocks in which this ratio is lower than in the staurolite schists fall in the field of garnet–biotite–muscovite. With increasing grade of regional metamorphism the mineralogy of such rocks remains unchanged until the *PT* conditions of the sillimanite zone of the upper amphibolite facies (Turner, 1968) are attained, during which muscovite breaks down to sillimanite and potash feldspar. Such a wide zone of garnet is common in Kumaon Himalaya (Lal, 1969).

TABLE I. *Chemical and modal analyses of pelitic schists of Kishangarh. Anal. R. K. Lal and R. S. Shukla*

	1	2	3	4	5	6	7
SiO_2	64·82	61·92	58·13	60·49	59·37	60·27	33·17
Al_2O_3	13·00	16·24	19·05	19·00	19·76	19·76	36·16
Fe_2O_3	12·72	9·94	3·13	2·55	3·69	3·10	5·33
FeO	0·80	1·36	6·23	5·47	6·05	5·60	9·14
MnO	tr	0·11	tr	tr	tr	tr	tr
MgO	0·11	0·30	3·45	3·96	4·27	3·20	7·59
CaO	1·63	2·14	1·35	1·26	0·22	0·40	0·20
Na_2O	2·60	3·40	2·15	2·00	0·70	1·85	0·60
K_2O	1·70	1·93	2·50	2·31	2·36	2·40	2·40
TiO_2	1·25	1·50	1·80	1·60	1·60	1·70	1·90
P_2O_5	0·01	0·00	0·07	0·07	0·06	0·13	0·02
H_2O+	0·54	0·91	1·21	1·43	1·62	1·50	2·99
Total	99·18	99·75	99·07	100·14	99·70	99·91	99·50
Rock oxidation ratio	93·4	86·5	30·6	28·3	35·4	32·7	34·2
Quartz	36·4	20·6	29·6	27·5	44·8	53·7	0·6
Plagioclase	33·0	49·0	32·1	29·3	5·5	5·7	—
Staurolite	—	—	8·1	13·3	19·5	13·4	40·3
Muscovite	17·1	20·6	0·1	0·2	0·1	0·1	7·1
Biotite	—	—	25·2	28·1	29·2	25·7	22·1
Garnet	—	1·0	0·3	0·6	—	0·3	—
Kyanite	—	—	—	—	—	—	8·2
Magnetite	2·1	3·2	4·0	0·1	0·4	0·4	2·1
Ilmenite	—	—	0·4	0·8	0·5	0·7	2·0
Hematite	10·5	5·5	—	—	—	—	—
Chlorite	+	+	+	0·1	+	+	11·1
Sericite	—	—	+	+	+	+	6·5

1. Muscovite schist
2. Muscovite-garnet schist
3, 4, and 6. Staurolite–biotite schists with sporadic garnet.
5. Staurolite–biotite schist
7. Staurolite–biotite–kyanite schist from contact of a quartz vein.

The AKF diagram also shows the effects of varying oxidation ratio[1] on the mineralogy of pelitic schists. With increasing oxidation ratio bulk rock composition migrates towards the muscovite–kyanite join. Pelitic rocks of high oxidation ratio are rich in kyanite, muscovite, opaques, and possibly chlorite, as shown by Hounslow and Moore (1967), and are represented close to the two-phase field of muscovite–kyanite in the AKF diagram (fig. 1). In the Kishangarh area, however, such oxidized

[1] $100 \times 2\,Fe_2O_3/(FeO+2Fe_2O_3)$; mol % (Chinner, 1960).

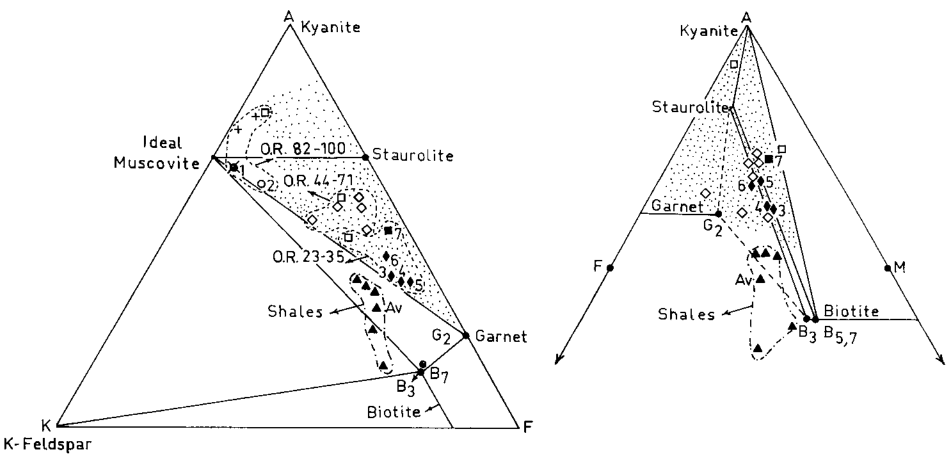
TABLE II. *Partial chemical analyses of the minerals from Kishangarh. Anal. R. K. Lal*

	Garnet	Staurolite		Biotite		
	G_2	St_7	St_3	B_7	B_3	B_5
Al_2O_3	22·80	51·95	nd	19·76	17·46	nd
FeO	16·90	10·66	10·66	10·50	10·50	9·80
MnO	10·00	nd	nd	0·09	0·12	0·00
MgO	8·93	3·06	3·00	13·52	12·00	12·50
CaO	1·60	nd	nd	nd	nd	nd
K_2O	nd	nd	nd	8·20	8·00	nd
TiO_2	0·74	0·74	1·05	1·47	1·54	0·76

G_2. Garnet from muscovite–garnet schist (no. 2, table I).

St_7 and St_3. Staurolites from staurolite–biotite–kyanite schist and staurolite–biotite schist with sporadic garnet (nos. 7 and 3, table I).

B_7, B_3, and B_5. Biotites from staurolite–biotite–kyanite schist, staurolite–biotite schist with sporadic garnet, and staurolite–biotite schist (sample nos. 7, 3, and 5, table I).



FIGS. 1 and 2: Fig. 1 (left). AKF diagram of staurolite schists and associated pelitic schists of Kishangarh and other areas. Stippled area represents the field of staurolite-bearing schists. ◆ kyanite-free staurolite–biotite schist, ± garnet, poor in muscovite; ◇ ditto, rich in muscovite; ■ kyanite-bearing staurolite schist, poor in muscovite; □ ditto, rich in muscovite; + kyanite–muscovite schist, rich in opaque 'ores'; ⋊●⋉ muscovite schist, rich in opaque 'ores'; ○ muscovite–garnet schist, rich in opaque 'ores'; ▲ shales; Av, average shale (Shaw, 1956); other analyses of shales from Pettijohn (1957, p. 362). Nos. 1–7 from Kishangarh area. G_2, B_3, and B_7 are analysis points of garnet (G) and biotites (B) from Kishangarh. Other analyses of pelitic schists (unnumbered) plotted in the diagram are from Hounslow and Moore (1967). Note that the staurolite-bearing schists, with or without kyanite and garnet, lie above the garnet–muscovite join (mainly within the triangle of staurolite–muscovite–garnet) and with increasing oxidation ratio the bulk composition of the rocks migrates towards the kyanite–muscovite line in the diagram. Fig. 2 (right). AFM diagram of staurolite-bearing schists of Kishangarh. Stippled area represents the field of staurolite schists. Analyses of staurolite-bearing rocks (unnumbered) from Hounslow and Moore (1967) are also plotted in the diagram. Key to symbols see fig. 1.

rocks contain less alumina (table I, sample nos. 1 and 2) and therefore lie close to the ideal muscovite composition and muscovite–garnet join. The complete absence of biotite and chlorite in these rocks may be related to low MgO content.

Garnet from the muscovite–garnet schist of the Kishangarh area has been analysed (table II), and contains 10 % MnO. Hounslow and Moore (1967) and Chinner (1960) have also reported similar garnet with high MnO content from highly oxidized pelitic schists. They have suggested that the residual FeO left after the formation of opaque 'ores' is very low in rocks with high oxidation ratio and hence the mineral becomes spessartine-rich. Garnets from less oxidized rocks are poorer in MnO (Chinner, 1960; Hounslow and Moore, 1967) and thus the large variation in spessartine content shows this variable is not a generally applicable indicator of metamorphic grade as suggested by Sturt (1962).

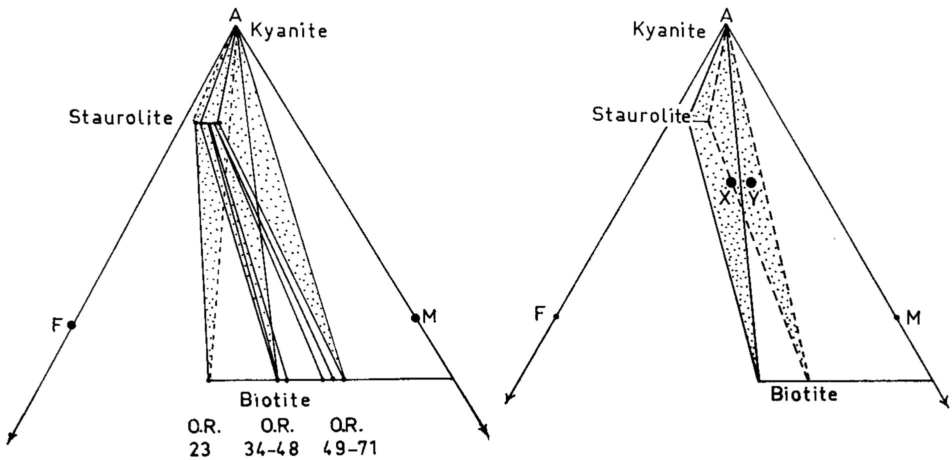
Although staurolite-bearing rocks have a general composition field in the AKF diagram, the various mineralogical assemblages are better represented in the Thompson's AFM diagram (fig. 2) in which FeO and MgO are considered as separate components. The staurolite–biotite schists of Kishangarh area (nos. 3, 4, 5, and 6), which contain sporadic amounts of garnet, fall close to the two-phase field of staurolite–biotite and have a narrow range of FeO/MgO ratio. Similarly, the staurolite–biotite–kyanite assemblage (no. 7) is represented in the three-phase field of staurolite–biotite–kyanite and the ratio of FeO/MgO is low as compared to the kyanite-free staurolite schists. A four-phase garnet–biotite–staurolite–kyanite assemblage, which apparently violates the requirements of the mineralogical phase rule, has been reported by Green (1963)[1] and Hounslow and Moore (1967). They have pointed out that common garnet is not a pure Fe-Mg garnet but contains appreciable amounts of Ca and Mn. Both these elements tend to remove the garnet from the AFM plane. Because the garnet structure readily takes in Ca, and especially Mn, almandine garnet is stabilized beyond the range of conditions of bulk composition represented in the diagram. It is thus possible that the presence of sufficient Mn stabilizes garnet as an extra phase in the assemblage kyanite–staurolite–biotite. If this statement is true, the sporadic occurrence of garnet in the staurolite–biotite schists of the Kishangarh area may be related to low Mn content of the rock (table I).

In the AFM diagram, the analyses of staurolite-bearing rocks of Kishangarh and other areas show that they have a high Al_2O_3 (excess)/(FeO+MgO) ratio compared with common argillaceous rocks. Further, the rocks have a variable FeO/MgO ratio and are not restricted to high FeO/MgO ratio as suggested by Turner and Verhoogen (1960), Winkler (1965), and others. On the basis of detailed chemical data on staurolite schists, Hounslow and Moore (1967) have demonstrated that the bulk composition field of staurolite-bearing rocks migrates towards the lower FeO/MgO side in the AFM diagram with increasing oxidation ratio (fig. 3). Thus in pelitic rocks with a lower oxidation ratio, the rock composition field of staurolite is restricted towards the higher FeO/MgO side in the AFM diagram and with increasing oxidation ratio the field widens.

Besides the oxidation ratio, the composition field of staurolite-bearing rocks also

[1] Instead of kyanite, andalusite occurs in the four-phase assemblage described by him.

migrates towards the higher FeO/MgO side in the AFM diagram with increasing grade of regional metamorphism (Chinner, 1965), assuming pressure and oxidation ratio to be constant (fig. 4). If the three-phase fields shown in the diagram represent the general case, then the mineralogy of a rock of given composition may vary depending upon the grade of metamorphism, e.g. the rock X, a staurolite–biotite schist, and Y, a staurolite–biotite–kyanite schist of relatively lower grade, will give rise to staurolite–kyanite–biotite and biotite–kyanite schists respectively in higher grades of metamorphism. Similarly, the shifting of the three-phase field may also account for the presence of the four-phase garnet–staurolite–biotite–kyanite assemblage.



FIGS. 3 and 4: Fig. 3 (left). The AFM diagram showing the shifting of the three phase staurolite–biotite–kyanite field (stippled) towards lower FeO/MgO side with increasing oxidation ratio (O.R.). Chemical analyses of minerals used in plotting are from Hounslow and Moore (1967). Fig. 4 (right). Schematic AFM diagram showing shifting of the three phase staurolite–biotite–kyanite field (stippled) towards higher FeO/MgO side with increasing grade of metamorphism, assuming pressure and oxidation ratio to be constant. Dashed and solid tie lines represent the assemblage from relatively lower and higher grade of metamorphism respectively. X and Y represent points of two hypothetical pelitic schists.

On the basis of the above discussion, it is suggested here that two factors have played important roles in the paragenesis of staurolite in pelitic schists of amphibolite facies:

In regional metamorphism staurolite commonly occurs in pelitic schists in staurolite–kyanite and sillimanite–muscovite zones of the amphibolite facies of Turner (1968), as stated already, suggesting a narrow range of its stability. Richardson (1967, 1968) has experimentally determined the lower and upper stability limits of staurolite in presence of quartz to be 500 to 550 °C and 675 to 700 °C respectively at fluid pressure greater than $1\frac{1}{2}$ kb. This is in agreement with the occurrence of staurolite in pelitic schists of the amphibolite facies.

Assuming that the *PT* conditions are within the stability field of staurolite, the mineral develops in pelitic schists in which the rocks have a high Al_2O_3 (excess)/

($K_2O+FeO+MgO$) ratio, so as to lie above the muscovite–garnet join in the AKF diagram and the ratios of Al_2O_3 (excess)/($FeO+MgO$) and FeO/MgO are such that the rocks lie within the composition field of staurolite schists in the AFM diagram. This field migrates towards the lower FeO/MgO side in the AFM diagram with increasing oxidation ratio. In rocks of similar oxidation ratio, the composition field of staurolite schists is progressively reduced because of shifting of the three-phase staurolite–biotite–kyanite field towards the higher FeO/MgO side in the AFM diagram with increasing grade of metamorphism. This may result in disappearance of staurolite by reactions involving mica and quartz, before the upper stability limit of staurolite–quartz is reached as suggested by Chinner (1965).

Acknowledgements. The authors wish to express their thanks to Drs. R. S. Sharma and B. K. Das of the Department of Geology, Banaras Hindu University, for critical discussion on the subject of this paper, and to Dr. S. G. Karkare for his help in the analytical work.

REFERENCES

CHINNER (G. A.), 1960. *Journ. Petrology*, **1**, 178.
—— 1965. *Min. Mag.* **34**, 132.
DEER (W. A.), HOWIE (R. A.), and ZUSSMAN (J.), 1962. *Rock-Forming Minerals*, **2**, London (Longmans).
GANGULI (J.), 1968. *Amer. Journ. Sci.* **266**, 277.
GREEN (J. C.), 1963. *Amer. Min.* **48**, 991.
HOUNSLOW (A. W.) and MOORE (J. M.), 1966. *Geological Paper 66–1*, Dept. of Geology, Carleton University, Ottawa, Canada.
—— —— 1967. *Journ. Petrology*, **8**, 1.
LAL (R. K.), 1969. *Publication of the Centre of Advanced study in Geology, Chandigarh, India*, no. 6, 55.
NIYOGI (D.), 1965. *Wadia commemorative volume, Mining, Geological & Metallurgical Institute of India*, p. 458.
PETTIJOHN (F. J.), 1957. *Sedimentary Rocks*, 2nd edn. (Harpers Brothers).
RICHARDSON (S. W.), 1967. *Geophysical Lab. Year Book*, **66**, 398.
—— 1968. *Journ. Petrology*, **9**, 467.
SHAPIRO (L.) and BRANNOCK (W. W.), 1956. *U.S. Geol. Surv. Bull.* **1036–C.**
—— —— 1962. Ibid. **1144–A.**
SHAW (D. M.), 1956. *Bull. Geol. Soc. Amer.* **67**, 919.
STURT (B. A.), 1962. *Journ. Petrology*, **3**, 181.
THOMPSON (J. B., Jr.), 1957. *Amer. Min.* **42**, 842.
TURNER (F. J.), 1968. *Metamorphic Petrology* (McGraw-Hill).
—— and VERHOOGEN (J.), 1960. *Igneous and Metamorphic Petrology* 2nd edn. (McGraw-Hill).
WINKLER (H. G. F.), 1965. *Petrogenesis of Metamorphic Rocks.* New York (Springer–Verlag).

[*Manuscript received 9 June 1969*]