# *Paragenesis of the metasomatic actinolite-bearing rocks from the Khetri copper belt, Rajasthan, India*[1]

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[Taken as read 12 January 1967]

*Summary.* In the south-eastern part of the Khetri copper belt, actinolite occurs in association with alteration assemblages resulting from the Fe–Mg metasomatism that accompanied sulphide mineralization, and more commonly with albite-bearing rocks formed by albitization of quartzites and schists near granitic rocks. Within the latter occur many coarse, massive, and unoriented aggregates of actinolite crystals, individuals being commonly more than 10 cm long. Locally fluorite-bearing veins occur within granitic and albite-quartz rocks. The actinolite is pleochroic from pale pink to green; $\gamma$: [001] = 26°; $\gamma = 1{\cdot}642 \pm 0{\cdot}003$; $2V_\alpha = 80°$. The composition of the analysed actinolite closely compares with those published in the literature excepting in (OH), which is low. The mineral assemblages, formed by metasomatic replacement of pre-existing rocks, are equivalent to those of albite–epidote–amphibolite facies. The metasomatic fluid was apparently rich in Ca, F (indicated by fluorite), and oxygen (indicated by magnetite, ilmenite, and hematite).

SULPHIDES in the Khetri copper belt, Jhunjhunu and Sikar districts, Rajasthan, have essentially been localized along shear and fault zones in quartzites, schists, and amphibolites (Roy Chowdhury and Das Gupta, 1965). Near sulphide bodies, the products of metasomatism and alteration include zones of Fe–Mg amphiboles (*viz.* anthophyllite, cummingtonite, ferrogedrite, and ferrocummingtonite), actinolite, chlorite, biotite, sericite, etc. In the south-eastern part of the Khetri belt, massive rocks composed of actinolite alone or of actinolite and albite occur within or near granitic rocks. Actinolite occurs in the mineralized shear zones in close association with the albite-bearing rocks where sulphides are rare. The mode of occurrence, the textural features, and the time relation between the crystallization of actinolite and albite show that this actinolite is formed by metasomatism during albitization that accompanied the emplacement of granitic rocks. Excepting in the metabasites and metamorphosed marly rocks, actinolite is generally absent in the country rocks.

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Actinolite is widely recognized as a product of metamorphism (cf. Deer *et al.*, 1963), and has also been recorded as a common gangue mineral in certain 'skarn' deposits; Macdonald (1941) described metasomatic actinolite from the Sierra Nevada of California, U.S.A. The metasomatically formed actinolite has added interest in that it is related to sulphide mineralization. This paper describes the mode of occurrence, mineralogy, and paragenesis of the actinolite-bearing rocks of the Khetri copper belt.

*Geological setting.* The area consists of a thick series of quartzites and pelitic schists interlayered with marble, and impure calcareous rocks metamorphosed into amphibole quartzites, amphibole gneisses, etc., belonging to the Alwar and the Ajabgarh Series of the Pre-Cambrian Delhi System of Heron (1923). The distribution of these two series and the associated granitic rocks along with the mineralized belts is shown in fig. 1. In places the rocks are traversed by the pre- and post-granite doleritic rocks, now metamorphosed to epidiorites and amphibolites. Together with the earlier basic rocks, the rocks of the two series have been complexly folded into doubly plunging anticlines with superposed folds whose axes plunge down dip of bedding, and with increasing intensity of stress the folds yielded into faults. Regionally the rocks are metamorphosed under conditions of the amphibolite and albite–epidote–amphibolite facies excepting along west central part, where rocks of lower facies occur. Synkinematic hornblende- and biotite-granite intrusions are followed by extensive post-kinematic albitization of the country rocks, especially near intrusives and dislocation zones. Here sulphide mineralization is mainly controlled by the fault and shear zones (Roy Chowdhury and Das Gupta, 1965, 1965*a*). Albitization took place simultaneously with and outlasted the sulphide mineralization.

*Mode of occurrence.* Actinolite is a common constituent of the brick-red albite-bearing rocks of the area; it occurs usually as massive aggregates and less commonly as discrete, well-developed coarse crystals lining cavities, fractures, etc. Locally decussate aggregates of actinolite transect the groundmass of finer grained actinolite. Near Salwari in the southern part of the belt, five actinolite-rich patches of various sizes and shapes have been mapped on a large scale (fig. 2, unpatterned areas represent covered grounds). Albite-bearing rocks or actinolite replace garnet–biotite schists (almandine, *n* 1·83) and quartzites; here actinolite occurs mainly with the albite-bearing rocks (Das Gupta, 1964*a*). The distribution of actinolite within the albite-bearing rocks is erratic. At places actinolite veins traverse the schists and quartzites

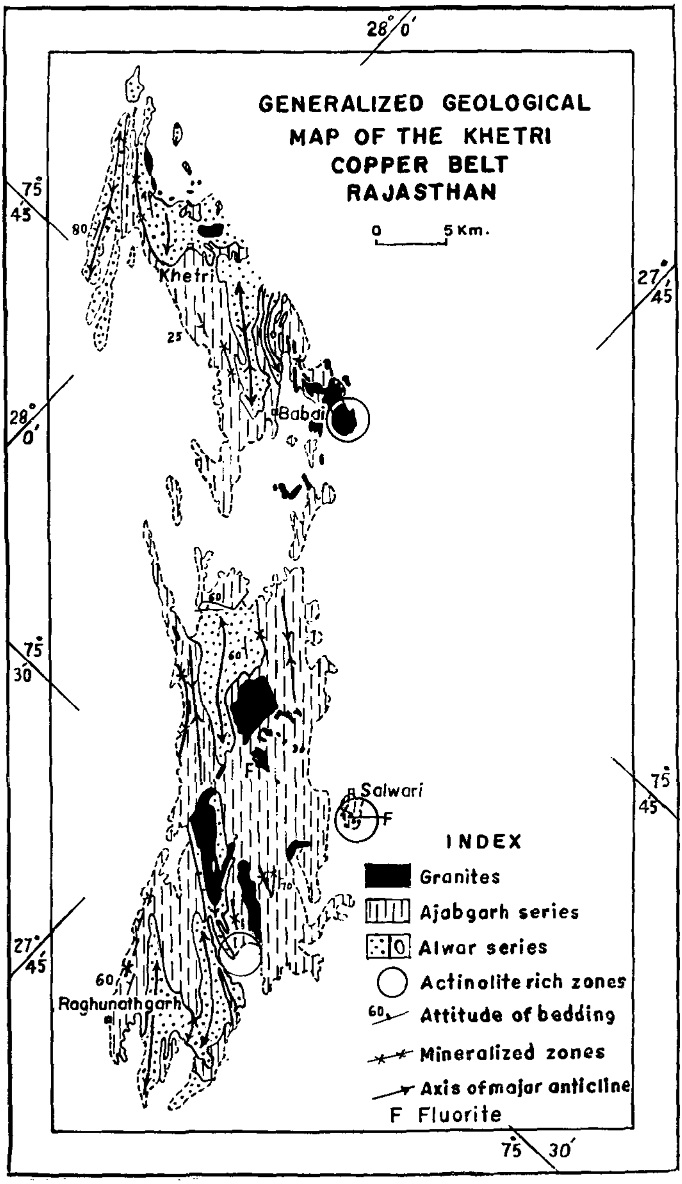
GENERALIZED GEOLOGICAL MAP OF THE KHETRI COPPER BELT RAJASTHAN
0 5 Km.
28° 0'
75° 45'
27° 45'
28° 0'
75° 30'
75° 45'
27° 45'
75° 30'
Khetri
Babai
Salwari
Raghunathgarh
80
25
60
F
INDEX
Granites
Ajabgarh series
Alwar series
Actinolite rich zones
Attitude of bedding
Mineralized zones
Axis of major anticline
F Fluorite

Fig. 1.

with or without albite. Often the actinolite rocks are traversed by younger quartz veins (2 mm to 3 m wide) with or without albite. The contacts between the albite-quartz rocks and the actinolite-bearing rocks are highly irregular; the latter metasomatically replace the earlier.

The quartzites that are replaced by actinolite are rich also in albite and magnetite; supergene chrysocolla is locally noted. Epidote, which is poor or absent in the rocks of the Salwari area, occurs about 7 km north of Salwari in the metasomatized quartzites and schists as albite–epidote–actinolite-bearing assemblages. In order of paragenetic sequence magnetite, ilmenite, hematite, and rutile occur profusely in actinolite-quartz rocks at Salwari. Chalcopyrite and pyrite are rare. Locally sphene, apatite, fluorite, scapolite, calcite, dolomite, and siderite are also present. Cleavelandite veins and masses transect the inclusion-free coarse albite ($An_{10}$) and actinolite that had crystallized earlier. The crystals of reddish brown cleavelandite, which are riddled with fine inclusions of hematite and magnetite, show ill-defined or diffused outline and chess-board twinning.

*Mineralogy of the actinolite.* Actinolite, quartz, magnetite, and ilmenite when they occur together are either automorphic or xenomorphic; in places small crystals of albite are developed. Less commonly actinolite occurs as perfect single crystals ranging in size from 0·1 to 150 mm long and 0·05 to 35 mm wide. Actinolite crystals commonly occur as short stout prismatic crystals, locally becoming slender. Rarely it occurs in diamond-shaped tablets owing to well developed {011}. The forms recognizable in well developed crystals are {100}, {010}, {001}, {110}, {130}, {011}, and {101}.

The mineralogical and chemical data of the analysed actinolite are given in table I. The specimen was collected from the southernmost outcrop of the actinolite mass at Salwari (fig. 2). Actinolite occurs in the assemblage actinolite–albite–quartz–magnetite–sphene–epidote of which actinolite constitutes about 85 %. The pure fraction was separated easily because the mineral occurs in coarse crystals free from inclusions of other minerals. The crystals were crushed to pass through 100-mesh A.S.T.M. sieve and separated on a Frantz Isodynamic Separator.

*Paragenesis.* The composition of the actinolite studied does not differ much from, and is closely comparable to the ideal formula excepting in (OH). $H_2O+$ content determined by standard Penfield method has been checked by repeated analyses. Apparently $(OH)'$ has been substituted by $F'$ but total $(OH,F)'$ is less than 2, the rest presumably being balanced by partial substitution of $O''$ (cf. Berry and Mason, 1959,

p. 521). (OH)′ deficient amphiboles have been recorded by Groves (1935) and others (*vide* Deer *et al.*, 1963, pp. 251, 316–17) but none of these are of high F′ compared to (OH)′. There are unfortunately few data on the F′ content of actinolites. Geijer (1960) determined the range from 0·40 to 1·17, the average being 0·63; but if more analyses were available it would certainly be much less. In the analysed specimen F′ is lower than Geijer's average but it is abnormally high to (OH)′ of the mineral.

TABLE I. Chemical analysis (A; analyst R. N. Sen Sarma) and atomic ratios to 24(O,OH,F) of actinolite from Salwari, Khetri copper belt, Rajasthan, India (the southernmost outcrop shown in fig. 2)

| | A | | B | |
|---|---|---|---|---|
| $SiO_2$ | 55·46 | Si | 7·94 | 8·00 |
| | | Al | 0·06 | |
| $Al_2O_3$ | 2·18 | Al | 0·31 | 5·328 |
| $TiO_2$ | 0·40 | Ti | 0·043 | |
| $Fe_2O_3$ | 2·80 | $Fe^{3+}$ | 0·301 | |
| MgO | 17·83 | Mg | 3·805 | |
| FeO | 7·20 | $Fe^{2+}$ | 0·862 | |
| MnO | 0·06 | Mn | 0·007 | |
| $Na_2O$ | 0·84 | Na | 0·232 | 2·072 |
| CaO | 11·60 | Ca | 1·78 | |
| $K_2O$ | 0·33 | K | 0·06 | |
| F | 0·51 | F | 0·23 | 0·85 |
| $H_2O+$ | 0·65 | OH | 0·62 | |
| $H_2O-$ | 0·10 | | | |
| Total | 99·96 | | | |
| O ≡ F | 0·21 | | | |
| | 99·75 | | | |

Sp. gr.: 3·18.
Cleavage: {110} good; parting ‖ {001}.
Twinning: {100} and {001} simple.
$\alpha$ 1·622±0·002, pale pink,
$\beta$ 1·632±0·003, pale green,
$\gamma$ 1·642±0·003, green.
Absorption $\gamma > \beta > \alpha$

A few crystals show faint gradational zoning.
$\gamma$: [001] = 26°; $2V_\alpha = 80°$.

Cell dimensions (D.R. Das Gupta):
$a$ 9·89±0·01 Å
$b$ 18·24±0·01 Å
$c$ 5·26±0·01 Å
$\beta$ 105°±0°30′
$Z = 2$.

Tremolite molecule = 81·58 % and ferro-tremolite molecule = 18·42 %.

The close association of fluorite with actinolite is noted in the area (cf. Das Gupta, 1960); a high F : OH is found in the actinolite where it is associated with fluorite. Fluorite occurs as irregular masses replacing, or along shear fractures traversing the albite–quartz rocks and granites. The distribution of uniformly disseminated fine crystals of fluorite in the host rocks suggests that F′ was apparently in uniform concentration in the fluids in its initial stages, but was subsequently fractionated and locally concentrated to form fluorite deposits.

Likewise the high O″ content in the actinolite is reflected by the hematite inclusions in albite, and the close association of magnetite, ilmenite, and hematite especially in the immediate neighbourhood of actinolite rock masses. Fluorite crystallized after the iron–titanium oxide minerals. These minerals are locally associated with minor amounts of pyrite and chalcopyrite. The addition of sulphur can bring an apparent high O″ content in the system under certain conditions set forth by Kullerud and Yoder (1963, 1964), but in the absence of significant amounts of sulphides compared to the oxide minerals it is suggested that sulphur could not have accomplished such a high state of oxidation prevalent throughout the area.

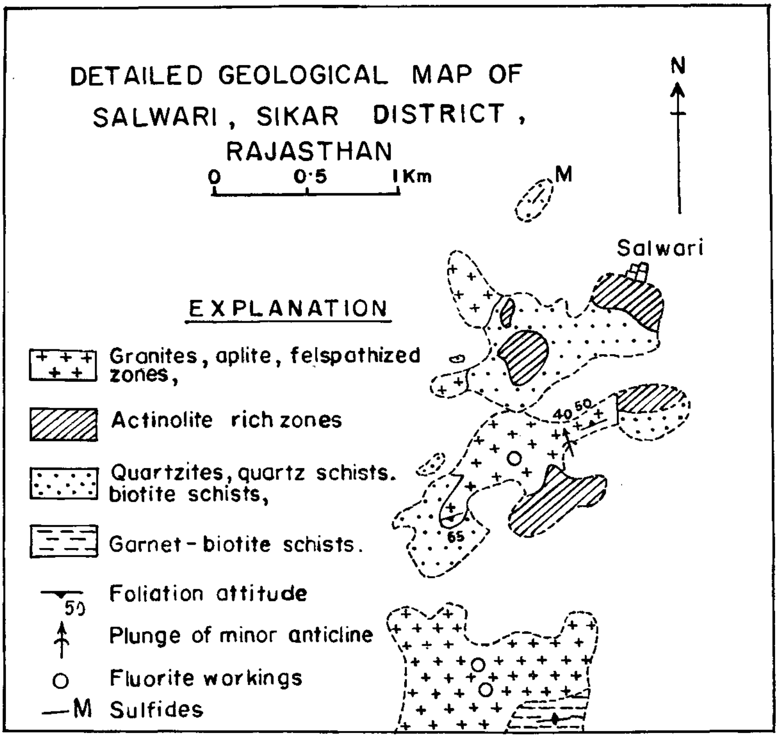

FIG. 2.

The temperature of formation of this deposit is lower than that of the amphibolite facies. The anthophyllite–cummingtonite-bearing rocks of the Khetri copper belt (Das Gupta, 1962, 1964) were formed under the physical conditions of the cordierite–anthophyllite subfacies of Eskola (Turner, 1949, pp. 76–88). The ratio of Fe : S in pyrrhotine (satisfying the conditions of Arnold, 1962) associated with the anthophyllite–cummingtonite-bearing rocks indicates a high temperature (about 450° C) of crystallization of the pyrrhotine (Das Gupta, 1964*b*). Anthophyllite–cummingtonite-bearing rocks are genetically associated with sulphides and crystallized earlier than the sulphides, and therefore the former are considered to be of high-temperature origin. Later actinolite, chlorite, etc., are in regressive sequence with that of the earlier anthophyllite, cummingtonite, etc., and therefore these later minerals are assumed to be of lower temperature of formation. Under amphibolite-facies conditions at high temperature and high water-vapour pressure, fluorine-bearing amphiboles would be unstable (Fyfe *et al.*, 1958, p. 162). The fluorine-rich, actinolite-bearing assemblages are lower in facies conditions characteristic of albite–epidote–amphibolite facies.

The change from Fe–Mg amphiboles to calcic amphibole zones has been marked with a fall in temperature and increase in $P_{H_2O}$ and $P_{O_2}$ during the change from amphibolite facies to albite–epidote–actinolite facies. At this stage concentration of Ca in the mineralizing fluid was apparently high as is indicated by the occurrence of actinolite, fluorite, calcite, etc.

*Acknowledgements.* The author is grateful to Dr. M. V. N. Murthy for drawing attention to the problem, the interest taken in the progress of work and the many suggestions in finalizing the work. The author is indebted to Dr. S. N. Sen and Dr. A. De of the University of Calcutta for stimulating and useful discussion on various aspects of the problem.

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[*Manuscript received 15 March 1966*]