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A study of the calc-gneisses, scapolite-gneisses, and cordierite-garnet-sillimanite-rocks of Coimbatore, Madras Presidency; with comparison to other similar occurrences in India.[1]

(With Plate V.)

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I. *Introduction.*

THE Indian peninsula, though considered to be a very stable part of the earth's crust and hence called the 'Indian Shield', shows in different parts evidence of formerly having sustained epi-continental basins, in which sedimentation occurred. These sediments are now found in detached prisms as crystalline gneisses and schists in different parts of India, e.g. in the Madras Presidency, Bihar and Orissa, Central Provinces, Central India, and Rajputana. They have been found overlying the ancient gneisses (Archaean), and belong to a division known in Indian geology as the Dharwar System.

The material to be described was collected in the Coimbatore district by the author in 1915, while a student of the Madras University. A short preliminary paper was read at the Geological Section of the Indian Science Congress held at Nagpur in 1920, and the work has since been completed by him as a research student in the Imperial College of Science and Technology, London.

[1] Published by permission of the Director, Geological Survey of India.

There are no published reports on the occurrence of these rocks in this part of the Madras Presidency, though Mr. C. S. Middlemiss made incidental mention of the calc-gneisses in his Presidential Address, 'Complexities of Archaean geology in India',[1] to the Geology Section of the Indian Science Congress at Bangalore, and also in 'The geology of the Idar State'.[2] But similar rocks collected over a century ago in the neighbouring district of Salem have been studied by A. Lacroix,[3] and the portion of his paper bearing on South India was translated by F. R. Mallet.[4] Lacroix's paper gives no definite information about the locality, so that it is not possible to ascertain the relation of the rocks he describes. He mentions the occurrence of biotite- and sillimanite-gneisses, and states that identical rocks occur in Salem and Ceylon.

II. *Geology of the area.*

The rocks forming the subject of this paper outcrop in low hills which rise towards the west. They can be divided into two distinct groups: (1) the cordierite-garnet-sillimanite-rocks (schistose, and in some places gneissose), and (2) the scapolite-gneisses with associated marble beds and calc-gneisses. The rocks of the plains consist mainly of biotite- and felspathic gneisses, which are not considered in this paper.

The rocks of the first group were at first called 'garnet-sillimanite-schists', but they are now described as cordierite-garnet-sillimanite-rocks, since cordierite has been found in them. They occur close to the railway station near Madukarai, a few hundred yards along the road to Coimbatore, and to the west they form the main mass of the Dharmalingham malai [hills]. They were traced as far as the Walayar river. The hills trend in a general ENE.–WSW. direction, and the foliation of the gneisses strikes NNE.–SSW.

The scapolite-gneiss is found overlying the last-named rocks on their northern and southern sides, forming two arms extending on either side of the Dharmalingham hills. The northern arm was traced only to a distance of 3–4 miles. The southern arm, occurring as detached outcrops in the form of small hills, was traced for a distance of 10–12 miles. Scapolite-gneiss also forms small hills in a

[1] C. S. Middlemiss, Journ. Asiatic Soc. Bengal, 1917, n. ser., vol. 13, pp. cxcv–ccii.

[2] C. S. Middlemiss, Mem. Geol. Survey India, 1921, vol. 44, pp. 42–43.

[3] A. Lacroix, Bull. Soc. Franç. Min., 1889, vol. 12, p. 282.

[4] A. Lacroix, Rec. Geol. Survey India, 1891, vol. 24, p. 155.

roughly elliptical area on the eastern side of the road from Madukarai to Coimbatore. Calc-gneisses are interbanded with the scapolite-gneiss.

The marble forms the base of the hills, weathering with smooth surfaces. It forms a marginal fringe of the eastern elliptical area of scapolite-gneiss, with a short extension to the west; and on the south

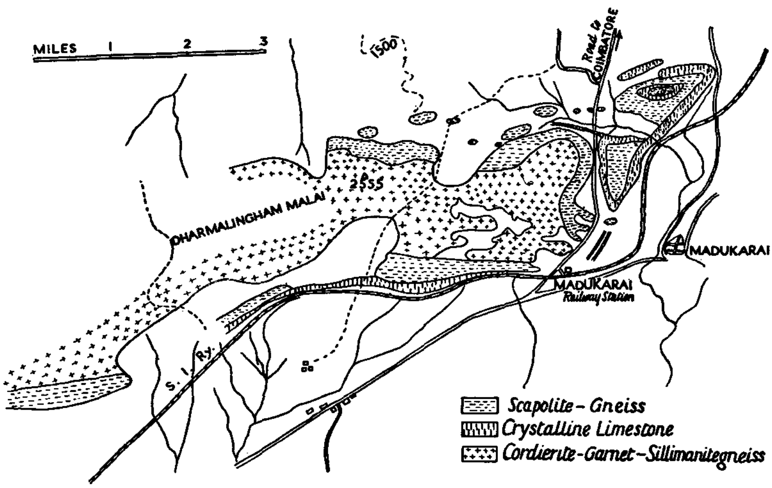

FIG. 1. Geological map of South Coimbatore taluk, Madras Presidency.

side of the Dharmalingham hills it extends for some distance along the railway line.

Pegmatite veins and lenses of quartz penetrate the cordierite-garnet-sillimanite-rocks and the crystalline limestone.

III. *The cordierite-garnet-sillimanite-rocks.*

General characters.—The texture and structure of these rocks vary in different localities. Sometimes they are more schistose, and at others they have a very coarse texture, with 'tabloid' aggregates composed of colourless minerals, such as sillimanite and quartz, occasionally associated with a little garnet, cordierite, and biotite. The 'tabloids' measure 2 to 3 in. in length, and are arranged along the direction of foliation, standing vertically, as seen near the railway station and near Karaipathy, $1\frac{1}{2}$ miles WNW. of the same locality. As these are composed of hard minerals, not easily disintegrated, they are found lying loose on the ground as the result of weathering. Sometimes the rocks are so fine grained that the 'tabloids' become very minute and are visible only under the microscope; they show no divisional planes.

Mineral composition.—The chief mineral components are quartz, biotite, sillimanite, garnet, cordierite, iron-ore, a little felspar, and some flakes of graphite. The cordierite present could not be detected in hand-specimens. The sillimanite and the biotite flow round and fold over the garnets, giving rise to 'augen' structure. The rock is sometimes greyish in colour (perhaps due to the grains of cordierite), or reddish-brown, exposing a large number of small, reddish, round garnets which weather out and strew the ground. The amount of biotite present varies in different localities.

The following rock types are represented by the specimens collected:

Specimen no. 2, from the line of hills a little NW. of Madukarai railway station. This is a very coarse grained garnetiferous sillimanite-schist and shows a very definite banding in the direction of the strike of the gneiss (NNE.–SSW.). It is brownish-red in colour, due to the coppery colour of the biotite. The 'tabloids', or platy aggregates of minerals, occur in abundance, standing out prominently on the surface of the rock. There are plenty of garnets among the sillimanite bundles, giving the 'augen' structure. The ground-fabric of these plates consists of quartz, biotite, garnet, iron-ore, and graphite.

Specimen no. 10 is one of the 'tabloids' picked from the weathered surface of the hill near Madukarai. Sillimanite needles are visible to the unaided eye; the garnets form the brown spots, round which curve the sillimanite bundles or needles. Biotite is present to a very small extent. Under the microscope the rock is seen to consist of bundles of sillimanite both as thick and needle-like crystals, and also as sheaf-like aggregates flowing round the pinkish garnet (pl. V, fig. 1).

Specimen no. 16 is a cordierite-garnet-biotite-sillimanite-gneiss from near Madukarai. This is also a greyish rock, rather fine grained and showing a definite foliation. The garnets are very minute and scattered. The structure of the rock is rather gneissose. Under the microscope it is a granoblastic, medium grained, banded rock made up mostly of colourless cordierite, quartz, and biotite. There is a little felspar, both orthoclase and albite being present. The biotite occurs as irregular brownish grains and at times as rectangular plates, oriented parallel to the direction of pressure. The garnet is pink, irregular elongated eye-shaped, and contains inclusions of quartz. The sillimanite occurs as hairy bunches or sheaves, as slender needle-shaped crystals, and as small needles in quartz.

Specimen no. 9 (pl. V, figs. 2 and 3) is another of the same rock, but more coarse grained than the above. It also shows regular banding, the biotites being arranged with their longer axes parallel to the foliation direction. There are also rounded and elongated eyes of garnet with bundles and fibres of sillimanite flowing round them. The garnets show also longitudinal cracks at right angles to the direction of foliation. A little albite showing characteristic twinning is also present, with an extinction-angle of 5–6°. Cordierite makes up the larger part of the rock, occurring as large plates having poikilitic inclusions of quartz. It shows a fine striation, its refractive index is lower than that of quartz or Canada-balsam, and it shows a very faint pleochroism.

The cordierite in these rocks is perfectly fresh and does not show any alteration to pinite, nor does it show pleochroic haloes or lamellar and sector polarization, which are usually present in this mineral. Further, it is optically positive, like the cordierite found by Mr. I. C. Chacko in Travancore in a dioritic rock [1]; and also described by Dr. M. S. Krishnan [2] from the Madura district of the Madras Presidency, where it is formed as a result of the contact metamorphism of an Archaean biotite-gneiss by an intrusive tongue of charnockite. The association of minerals also seems to be identical in this occurrence, since cordierite in varying proportions occurs with pinkish garnets, sillimanite, magnetite, titanoferrite, orthoclase, and oligoclase.

IV. *The scapolite-gneiss.*

Weathering, joints, and folding.—The action of the weather seems to have had a greater effect on the scapolite-gneiss. It is found grooved along the foliation direction. Abundant garnets stand out on the surface, and they are arranged in the direction of foliation. The scapolite-gneiss shows a very marked jointing, appearing rather slaty at a distance, owing to the grooved nature of the surface and the joint-planes. There is no cleavage as in slates, and joints are due to

[1] I. C. Chacko, Geol. Mag., 1916, dec. 6, vol. 3, p. 462.
[2] M. S. Krishnan, Min. Mag., 1924, vol. 20, p. 248.

tension during the folding. The joints have also been affected by the folding, for they show anticlinal and synclinal structures. Such complex folding can be seen in the detached blocks as well as on the hills themselves. Near the sixth milestone from Coimbatore to Madukarai huge well-jointed blocks of the rock are seen in large numbers (fig. 2). Numerous kinds of complex folding are visible in the detached blocks, but the main direction of the joint-planes runs along the foliation direction. The rock also breaks in thick slabs, sometimes flat, or sometimes curved if the joint-planes show folding. In this locality garnets are so abundant that they strew the ground at the base of the hills. They are generally small, but in the NE. corner of the hill they are of large size, about 2–3 in. in diameter.

The scapolite-gneiss does not vary in appearance. It is a greyish rock, very compact, and medium to fine grained. The ferromagnesian minerals appear as small spots, following the gneissic structure. The weathered surface effervesces slightly with acid owing to the presence of calcite.

Rock types.—A specimen from Madukarai is grey and white in colour and granoblastic with medium to fine grain. The chief minerals are a bright-green augite, plagioclase felspar, quartz, scapolite, calcite, sphene, and iron-ore. Under the microscope (pl. V, fig. 4) it is even grained and granulitic, showing banding. The colourless minerals are scapolite, calcite, and quartz, which form the greater part of the rock. The scapolite occurs as large, rectangular or square idioblastic plates, showing the characteristic cleavage, refractive index, birefringence, and straight extinction. Basal sections show two sets of cleavage and a good uniaxial figure. It is also present as inclusions in pyroxene, and at times is surrounded by the felspars. The scapolite itself has some inclusions of quartz. Quartz occurs interstitially as large elongated grains and has longitudinal cracks, showing that it was subjected to lateral pressure. Calcite is less common and occurs interstitially between the pyroxenes and scapolite, or often surrounding the latter. The felspar is mostly albite or oligoclase, and its long twin-lamellae have an extinction-angle of 10–14°. It occurs interstitially and sometimes enclosing the scapolite crystals. One large idioblastic crystal of felspar is seen enclosing scapolite. A few grains of apatite are also present. Among the ferromagnesian minerals, a green diopside, often paramorphosing into hornblende, is very common. The hornblende shows the characteristic basal sections, pleochroism from green to brown, and an extinction-angle of 15°. Sphene occurs as irregular and idioblastic grains. A few grains of garnet and a little biotite and magnetite are also present. Crystalloblastic order: magnetite, sphene, apatite, part of scapolite, pyroxenes, scapolite, felspar, and quartz.

Another interesting micro-section (pl. V, fig. 5) of these rocks is mostly made up of quartz, felspars (oligoclase and albite), pyroxenes,

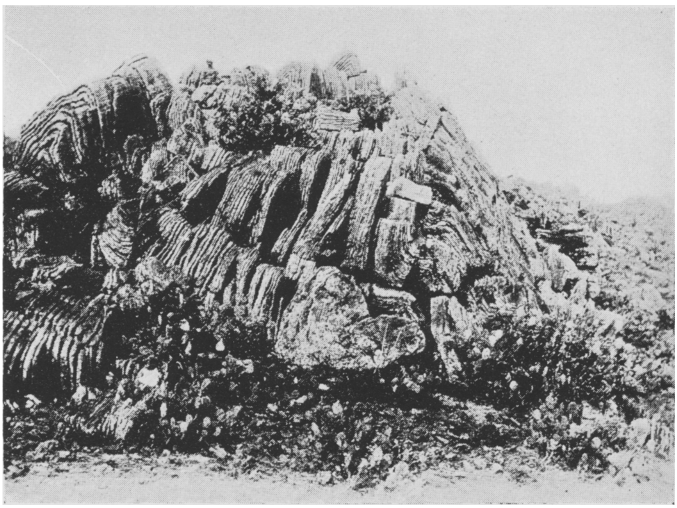

Fig. 2. Folding in scapolite-gneiss, near Madukarai, Coimbatore. [From 'Geography of the Madras Presidency', by E. Thurston. With permission of the Cambridge University Press.]

and a little calcite. The felspar is both twinned and untwinned, and is more abundant than in the previous rock, occurring as elongated plates. This rock is entirely free from scapolite. The pyroxene contains veins of calcite and quartz, perhaps produced during the alteration of pyroxene to hornblende. Felspars consist of both oligoclase and albite, which have extinction-angles of 5–10°. The pyroxene is dark green in colour, with less strongly coloured margins and interiors. It also contains inclusions of quartz and felspars. Crystalloblastic order: apatite, sphene, part of quartz and felspar, pyroxenes, felspars, and quartz.

This rock is really the result of recrystallization due to metamorphism in which the scapolite has been altered into felspars and pyroxenes. Evidence for this is given by the presence of quartz-felspar intergrowths ('quartz de corrosion' or myrmekite) on the margins of most of the felspar crystals. A similar phenomenon, with felspars forming a considerable part of the rock when no scapolite is present, has also been recorded by Adams and Barlow.[1] In the calc-gneisses of the Central Provinces in India, R. C. Burton [2] connects the refusion of similar rocks during metamorphism with the presence of vermicular inclusions of quartz.

V. *The crystalline limestone and calc-gneiss.*

The limestone grades from coarsely crystalline to fine in texture, and in colour through grey, pink, and white. Under the microscope (pl. V, fig. 6) the rock is medium to coarse grained, mostly made up of crystalline calcite having irregular edges. Twin-lamellae are not always developed. Some of the limestones are free from the lime silicate minerals, but in others their gradual development could be traced; the rock then grading into a calc-gneiss and often interbanded with the scapolite-gneiss. The pyroxenes begin to grow as small round grains in the calcite and gradually attain a larger size. Hornblende is also formed at times directly from the limestone, and so also a little biotite. Besides the above, small amounts of apatite, magnetite, sphene, and ilmenite altering to leucoxene are also present. The effect of pressure is evident, for the quartz shows undulose extinction, and the twin-lamellae in the calcite are sometimes bent and twisted.

VI. *Occurrence of similar rocks in other parts of India.*

Madras Presidency.—The occurrence of similar rocks in the Salem district has already been referred to. The next occurrence of these rocks is in the Ganjam and Vizagapatam districts, recorded by Dr. T. L. Walker.[3] Here the rocks consist of quartz, garnet, sillimanite, and graphite, and they form well-defined schists. He considers them as apparently altered sediments, overlying the granitoid gneiss, charnockite, and more massive gneisses of the crystalline complex. He has also recorded the occurrence of garnetiferous quartzite and calc-gneisses, interbanded with the sillimanite-rocks. The association of the sillimanite-schist with these rocks is thought to

[1] F. D. Adams and A. E. Barlow, Geology of Bancroft and Halliburton areas, Province of Ontario. Geol. Survey Canada, 1910, Mem. no. 6, pp. 102–113.

[2] R. C. Burton, Rec. Geol. Survey India, 1915, vol. 45, p. 102.

[3] T. L. Walker. Mem. Geol. Survey India, 1901, vol. 33, p. 8.

be an additional reason for regarding them as para-schists; while their occurrence above massive igneous rocks (charnockites, &c.) suggests that they are rocks formed by the metamorphism of ancient sediments.

The late Mr. E. W. Vredenburg [1] has mentioned that the khondalite and the Bezwada gneiss are identical, and describes them as consisting of quartz, sillimanite, and graphite; but W. B. King and R. B. Foote [2] do not mention the presence of sillimanite in the Bezwada gneiss, which they define as a quartzo-felspathic micaceous schist. Dr. King called it a murchisonite-gneiss. The abundance of murchisonite and the absence of sillimanite make it doubtful whether the Bezwada gneiss and the khondalites are identical.

In connexion with the manganese ores at Kodur, Dr. L. L. Fermor [3] mentions the occurrence of khondalites. Here also the calc-rocks are found next to khondalites.

Central Provinces.—Another occurrence of the garnet-sillimanite-rocks has also been recorded by Dr. Fermor in the Sausar tahsil.[4] He describes the gneisses in this area as ortho-gneisses, consisting of felspars (microcline, orthoclase, oligoclase, and labradorite), garnets in some places, and occasionally sillimanite. These are considered to have resulted from pressure on the original gneiss, and are not to be taken as any indication of the presence of assimilated sediments. R. C. Burton [5] has considered some of the gneisses to be crush conglomerates, in which flat, ellipsoidal, and tabloid bodies have been developed in biotite-granite and gneisses as the result of crushing.

With regard to certain of these garnet-sillimanite-gneisses or schists, and the finer grained biotite-gneisses, W. D. West [6] suggested that the rocks of these two horizons may be metamorphosed sediments. Later, in 1926, when the field relations of some of these gneisses had become better understood, he stated that the variety of muscovite-biotite-gneiss, which contains small tabloids rich in sillimanite, occurs always at the base of the dolomite suite and nowhere else, and that chemical analysis has proved it to be a para-gneiss.[7]

[1] E. W. Vredenburg, A summary of the geology of India, 2nd edit., 1910, p. 14.

[2] W. B. King and R. B. Foote, Mem. Geol. Survey India, 1879, vol. 16, pp. 12–14.

[3] L. L. Fermor, Ibid., 1909, vol. 37, p. 1046.

[4] L. L. Fermor, Rec. Geol. Survey India, 1916, vol. 47, pp. 34–35.

[5] R. C. Burton, Ibid., 1915, vol. 45, p. 133.

[6] W. D. West, Ibid., 1925, vol. 59, pp. 75–81.

[7] General Report, Ibid., 1926, vol. 60, p. 97.

Calc-gneisses.—Madras Presidency.—Calc-gneisses have been described by Dr. Walker in the Ganjam and Vizagapatam districts in connexion with the khondalites. The frequent association of the charnockite series with scapolite- and calc-gneisses is also mentioned by Sir T. H. Holland,[1] but he says that for want of field evidence bearing on the relation of these rocks to the charnockite series it is not possible to decide the origin of the accessory minerals. Dr. Fermor has also described them in connexion with the manganese ores of the Vizagapatam district. At Chintelavalsa in the same district the rock is a wollastonite-gneiss, and at another a scapolite-gneiss composed of scapolite and a green pyroxene with some untwinned felspar, calcite, and sphene.[2] Thus the calc-gneisses in all these areas show that they must have been formed by the metamorphism of impure calcareous sediments, and Dr. Fermor states that the scapolite-bearing rocks are to be considered as belonging to the series of the khondalites. The origin of the calc-gneiss and the crystalline limestone has been a subject of controversy. Professor J. W. Judd[3] in 1896 advanced reasons for believing that the crystalline limestone of Upper Burma was formed chemically from pre-existing basic gneisses.

Central Provinces.—This theory was considered to hold good in the case of the Chindwara district by Dr. Fermor,[4] who ascribed the origin of the crystalline limestone to the chemical alteration of pre-existing rocks containing an abundance of lime-felspars and magnesium silicates, the agent being carbon dioxide in solution; but further work enabled him and the late Mr. Burton to come to the conclusion that they must have been derived from a series of sediments by processes of metamorphism. This controversy has been summarized by Mr. C. S. Middlemiss in his paper 'Complexities of Archaean geology in India'.[5]

Idar State.—Mr. Middlemiss[6] has come across similar rocks in the Idar State, and fortunately in one place, in the proximity of an intrusion of Idar granite, he has traced a crystalline limestone passing

[1] T. H. Holland, Mem. Geol. Survey India, 1900, vol. 28, p. 232.

[2] L. L. Fermor, Ibid., 1909, vol. 37, p. 1112.

[3] C. B. Brown and J. W. Judd, Phil. Trans. Roy. Soc., 1896, vol. 187, p. 205.

[4] L. L. Fermor, Rec. Geol. Survey India, 1915, vol. 45, p. 100, and 1906, vol. 33, pp. 166–171.

[5] C. S. Middlemiss, Journ. Asiatic Soc. Bengal, 1917, n. ser., vol. 13, pp. cxcv–ccii.

[6] C. S. Middlemiss, Mem. Geol. Survey India, 1921, vol. 44, p. 59.

into undoubted sedimentary rock. At other places he finds only the completely metamorphosed derivatives. In other areas in India the metamorphism has been so intense that no remnants of the original rock have been left to show a transition from the unmetamorphosed to the crystalline rock; but in Idar evidence for both is available.

Adams and Barlow [1] have traced the action of granite intrusions on limestones, and they have described rocks of similar origin, passing from a calc-silicate-scapolite-rock into a granular pyroxene-rock with some scapolite, and into pyroxene-gneisses and amphibolites.

VII. *Metamorphism in these rocks.*

From a consideration of the several occurrences in India of this suite of rocks, it becomes evident that in Coimbatore we have quite a similar suite of rocks, derived from almost similar sedimentary rocks by processes of metamorphism. Now it has been suggested that there is no reason to believe that they are ortho-gneisses derived from igneous rocks. But in the case of the calc-gneisses, the metamorphism has been observed to be due to 'lit-par-lit' intrusion of an acid magma, or the action of an intrusive granite as in the case in Idar State. The garnet-sillimanite-rocks bring in also other important types of metamorphism.

Dr. T. L. Walker (loc. cit., 1901), instead of adhering to the cumbrous name of garnet-sillimanite-gneisses or schists, has given them a simpler name, 'khondalite', since they were found in the country of the Khonds. The cordierite-garnet-sillimanite-gneiss in Coimbatore forms quite a distinct metamorphic facies, since it contains both biotite and cordierite. The khondalites must have been derived essentially from arenaceous rocks, whereas the Coimbatore rocks must have been derived from argillaceous rocks. To replace the cumbrous name 'cordierite-biotite-garnet-sillimanite-gneisses', if I may follow the example of Dr. Walker without further burdening Indian geological terminology, I would suggest that these rocks be called 'madukarite', since they were discovered near Madukarai.

With regard to the calc-gneisses of the area, they have not been mixed with the biotite-gneisses as in other areas: there is no positive evidence that they are hybrid gneisses. The only evidence of igneous intrusion in these rocks is the presence of pegmatite and quartz veins in the crystalline limestone, but these have not been met with in the

[1] F. D. Adams and A. E. Barlow, loc. cit., 1910, pp. 87, 88.

scapolite-gneiss. Moreover, crystalline limestone has been found to be intercalated with the scapolite-gneiss, the one passing into the other. The gradation implies a gradual change in the composition of the calcareous sediments, or the alternation of layers differing in composition. But it cannot be denied that the intrusion of the neighbouring masses of the charnockites and gneisses must have influenced the metamorphic processes of the area considerably.

The metamorphic processes.—The study of these rocks would be incomplete without a consideration of the metamorphic processes involved in their formation. Since the three factors of temperature, pressure, and chemical environment (or the chemical composition of the original material) have impressed quite distinctive features on the metamorphic derivatives, the nature of the metamorphic facies enables us to trace back the course of metamorphism and to form conclusions concerning the nature of the original material.

The crystalline metamorphic rocks herein discussed are of two facies: (1) the cordierite-garnet-sillimanite-rocks, and (2) the scapolite-gneisses and the calc-gneisses. Taking the mineral composition, structure, and texture of these rocks into consideration, it is possible to trace the nature of the metamorphism and the facies of the original rock.

The cordierite-garnet-sillimanite-rocks by the nature of their mineral constituents show that they belong to the katazone[1] representatives of Grubenmann and Niggli[2] formed from pelitic schists. The conditions for the production of these katazone products are high temperature and very great uniform pressure, directed pressure being feeble or absent. The nature of the metamorphism involved is 'load' or static metamorphism; in other words, plutonic metamorphism, which is characterized by the production of anti-stress minerals, of which cordierite and sillimanite preponderate in this rock. The other chief constituents of this rock are biotite and garnet. The garnets occur as small red spots very uniformly distributed and can be considered as a product of metamorphism in the infra-plutonic zone.[3]

The artificial formation of cordierite and sillimanite in alumino-silicate melts of the general formula $RO.mAl_2O_3.nSiO_2$ has been

[1] G. W. Tyrrell, The principles of petrology, 1926, p. 258.

[2] U. Grubenmann and P. Niggli, Die Gesteinsmetamorphose, 1924, pp. 375–390.

[3] L. L. Fermor, Garnet as a geological barometer, Rec. Geol. Survey India, 1913, vol. 43, pp. 41–44.

studied by J. Morozewicz (1898). He found that if Fe and Mg are absent and if n is greater than 6, then sillimanite or sillimanite and corundum will form. When Fe and Mg are present and with n less than 6, then spinel or spinel and corundum are produced; with n greater than 6, the magnesia and excess of alumina give rise to cordierite or cordierite and spinel.

In a study of the paragenesis of the system $MgO–Al_2O_3–SiO_2$ by the investigation of melts, Grubenmann and Niggli show that cordierite, sillimanite, and quartz are formed below 1425°. The temperature for the formation of sillimanite was found to be 1000° at a pressure of one atmosphere, and 1320–1380° when formed from kyanite. It is also observed that in a magma or a sediment at great depth the assemblage quartz, sillimanite, and enstatite will not be stable, and may be transformed to the system cordierite, quartz, and sillimanite:

$$\underset{\text{Quartz}}{SiO_2} + \underset{\text{Sillimanite}}{2Al_2SiO_5} + \underset{\text{Enstatite}}{2MgSiO_3} \rightarrow \underset{\text{Cordierite}}{Mg_2Al_4Si_5O_{18}}.$$

The paragenesis in the katazone of the system $MgO–Al_2O_3–CaO$, with quartz as a fourth phase, is also dealt with in figs. 91 and 92 of Grubenmann and Niggli (loc. cit.). With the addition of iron and alkalis (in felspars), alkalis and water promote the formation of biotite if there is high alumina content. So the first field of the katazone paragenesis consists of quartz, potash-felspar, biotite, plagioclase, sillimanite, and cordierite. The ilmenite in the katazone goes in the presence of any available lime to sphene and magnetite.

Thus the cordierite-garnet-biotite-sillimanite-gneiss presents all the features of katazone paragenesis, while the presence of garnet indicates infra-plutonic metamorphism. Since the garnet contains inclusions of quartz and biotite, it must be considered to have formed as a later product of recrystallization. Considering the banded and foliated structure, and the elongated and longitudinally fractured garnets and quartz grains, it is evident that there has been a strong pressure at right angles to the direction of foliation in this rock. Thus these rocks show that there has been thermal or infra-plutonic metamorphism followed or accompanied by regional or dynamo-thermal metamorphism.

The effects of these two forms of metamorphism on the accompanying calc-gneisses may now be considered. The mineral constituents of these rocks comprise quartz, calcite, scapolite, pyroxene, a little felspar, apatite, sphene, and iron-ore. The origin of scapolite is not always easy to trace. In the case of the crystalline limestone of Burma, Professor J. W. Judd attributed it to the alteration of the plagioclase felspar. It has also been attributed to contact pneumatolytic reactions between igneous rocks and limestones. Sir T. H. Holland[1] in his paper, 'On the origin and growth of garnets', has mentioned that scapolite is conspicuous amongst the new minerals, where earth movements have been preceded by the production of sodium chloride inclusions along the twin-planes of the felspars. Mr. Vredenburg[2] has recorded the production of scapolite from the felspar due to the action of chlorine vapours passing along a fissure during the cooling of the rock in a trap dike in the Godavery district.

In the case of the calc-gneisses of the Central Provinces a limited contact-metamorphism has been attributed to 'lit-par-lit' intrusion of an acid magma. In the Coimbatore district, thin veins of pegmatite and quartz imply the proximity of an igneous intrusion, though no 'lit-par-lit' intrusion is found. On examining thin sections of these rocks for the crystalloblastic order, scapolite is one of the earliest minerals to form; it occurs as idioblastic crystals and as inclusions in the pyroxenes and the felspar. It forms a considerable part of the rock, and is very fresh and undecomposed. So it is difficult to prove that it has been formed by the alteration of a plagioclase felspar. The only explanation is that it must have been formed when the limestone was affected by thermal metamorphism, in which it must have been involved, as is proved by the local presence of garnets. The structure of the rock, the joints due to pressure and folding, orientation of the garnet on the rock surface, and the mineral arrangement in the rock sections as revealed by the microscope, show that dynamo-metamorphism or regional metamorphism had also a share in the metamorphism of these rocks. As a consequence, quartz grains and calcite show strain polarization, the quartz and scapolite are elongated in the direction of foliation, and the former has developed longitudinal cracks. The additional elements required for the formation of such minerals as scapolite, felspars, biotite, &c., must have been either present in the original rocks or introduced during the plutonic phase of the metamorphism.

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[1] T. H. Holland, Rec. Geol. Survey India, 1896, vol. 29, p. 23.
[2] E. W. Vredenburg, Ibid., 1904, vol. 31, p. 233.

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EXPLANATION OF PLATE V.

Gneisses from Coimbatore, Madras. Crossed nicols (except fig. 2).
Magnification 17 diameters.

FIG. 1. 'Tabloid' aggregate of sillimanite, cordierite, quartz, graphite, &c. (Specimen no. 10, p. 124.)

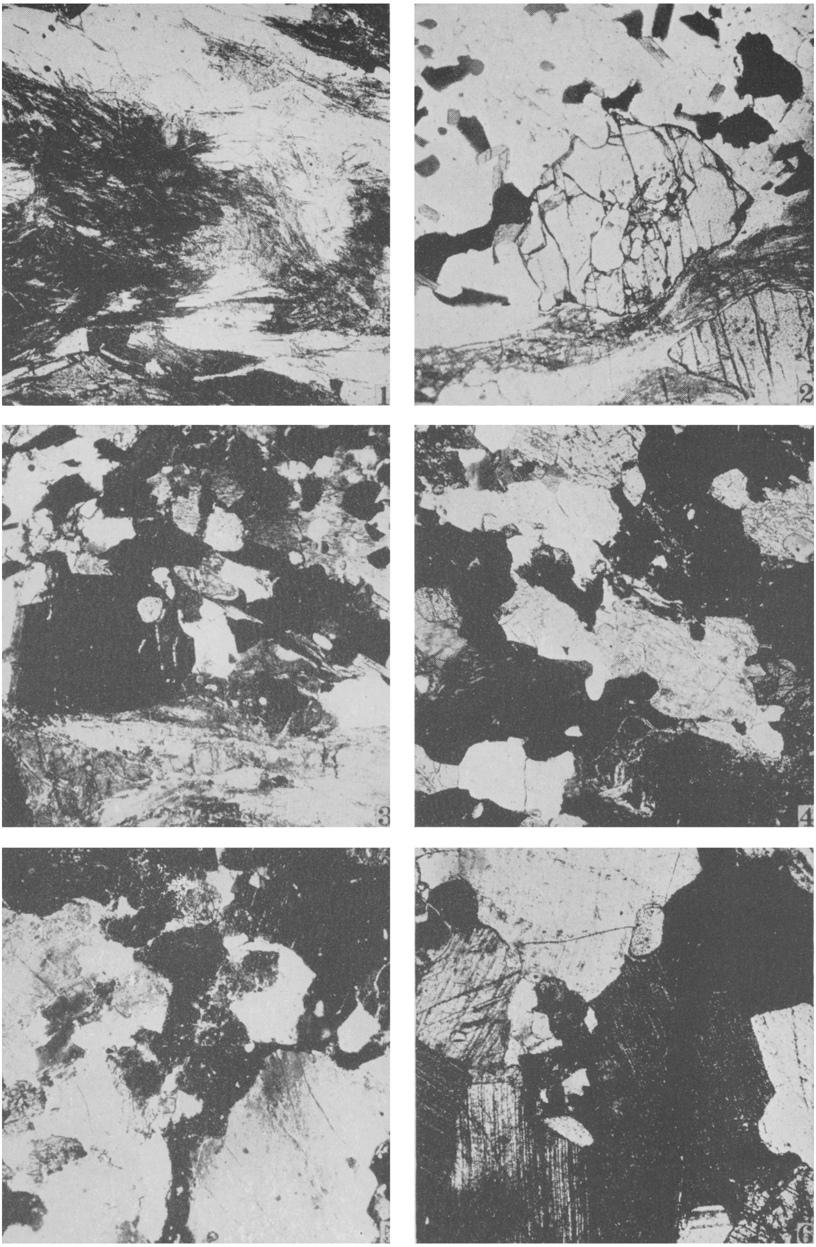
2. Cordierite-garnet-sillimanite-gneiss (madukarite), showing cordierite, garnet, sillimanite, biotite, and quartz. (No. 9, p. 125.)

3. Cordierite-garnet-sillimanite-gneiss (madukarite), showing poikilitic plates of cordierite with inclusions of quartz and biotite. (No. 9, p. 125.)

4. Scapolite-gneiss, containing diopside, large plates of scapolite showing cleavage, quartz, sphene, &c. (p. 126.)

5. Recrystallized calc-gneiss, consisting mostly of felspars showing undulose extinction, quartz, and diopside. The felspars have 'quartz de corrosion' (myrmekite) along their edges. (p. 127.)

6. Coarse-grained calc-gneiss, consisting mostly of crystalline calcite, in which diopside, hornblende, and sphene are formed. (p. 128.)



L. A. NARAYANA IYER: GNEISSES FROM COIMBATORE.