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Talc–kyanite–quartz schists and other high-pressure assemblages from Zambia[1]

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SUMMARY. Talc–kyanite–quartz schists, Mg-chlorite–kyanite–quartz schists, kyanite gedritites, and kyanite–bronzite gedritites occur in the Central Province of Zambia. Experimental work in the system $MgO–Al_2O_3–SiO_2–H_2O$ suggests that these assemblages formed at pressures in excess of 10 kb.

THE present paper was largely stimulated by the work of Schreyer and Seifert (1969) in the system $MgO–Al_2O_3–SiO_2–H_2O$ at high pressures. They showed that the lower-pressure boundary of the stability field of the assemblage talc–kyanite is at approximately 10 kb and is largely independent of temperature. The talc–kyanite association is therefore of special interest as an indicator of a high-pressure metamorphic environment. The yoderite-bearing talc–kyanite–quartz schist from Mautia Hill, Tanzania (McKie, 1958) is, as far as the authors are aware, the only previously described natural occurrence of this assemblage.[3]

Talc–kyanite–quartz assemblages from the Central Province of Zambia occur in a group of schists of unusual composition associated with epidote-rich amygdaloidal lavas, tuffs, and epiclastic rocks. They have been grouped with these rocks as the Rufunsa Metavolcanic Formation, which forms part of the pre-Katanga Mpanshya Group (Barr, in prep.), and which crops out extensively in central and eastern Zambia. Most of the schists contain Mg-chlorite as the main ferromagnesian mineral, often accompanied by kyanite, or by biotite, hornblende, plagioclase, and epidote in the more basic varieties. Hematite is frequently present, usually accompanied by rutile. The high oxygen fugacity indicated by the oxide mineral assemblages has led to the suppression of ferrous-iron-bearing silicates in the more aluminous and magnesian schists. The most extensive occurrence of talc–kyanite–quartz schist within this unit is on and around Chilapila Hill, 29° 22′ E., 15° 39′ S., overlooking the Zambesi river, but similar assemblages also occur at scattered localities up to 25 km to the north and west.

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[3] After this paper was submitted, our attention was drawn to the occurrence of the talc–kyanite assemblage in the Allalin metagabbro in the Swiss Alps (G. A. Chinner and J. E. Dixon, in preparation).

The samples on which this study is based were collected in the normal course of reconnaissance mapping of the area. Because of its remoteness, it has not proved possible to return to Chilapila Hill for more detailed sampling.

Preliminary information on new occurrences of related rocks, i.e. Mg-chlorite–kyanite–quartz schists and kyanite-bearing gedritites, some of which occur with talc–kyanite schist, and on kyanite–bronzite-bearing rocks, is included. These rocks are similar to the talc–kyanite schists in their chemical composition and crystallized under similarly high-pressure conditions.

Talc–kyanite–quartz schists

Petrography. The talc–kyanite–quartz schists are fine-grained homogeneous rocks, greyish-white in colour. A well-developed preferred orientation of the talc imparts a distinct mineral lineation to the schists; one sample (8HC 459)[1] shows a strong planar fabric. The schists are composed of interlocking flakes of talc (0·2–1·0 mm), equant grains of quartz (0·1–0·5 mm), and kyanite. The smaller grains of kyanite, especially when in contact with talc, tend to be idioblastic (fig. 1), while some porphyroblastic crystals are strongly poikiloblastic, enclosing quartz, talc, and hematite. In the coarse fraction of crushed samples, kyanite was observed in the form of greyish-white to colourless slender prisms 1 to 3 mm long. Minute hematite grains, tabular or irregular in shape, and brown-red rutile are ubiquitous accessories. Tourmaline may occur in the form of nearly equant grains.

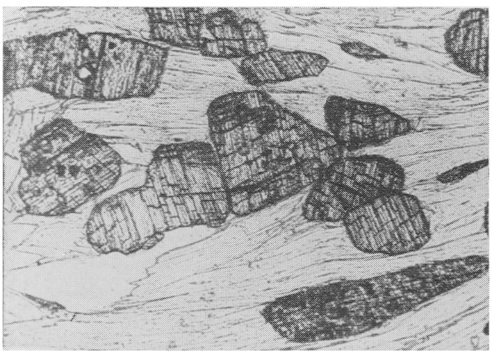


FIG. 1. Talc–kyanite–Mg-chlorite–quartz schist (8HC 459). Retrogressive Mg-chlorite is absent from this photomicrograph; 1 polar, ×37.

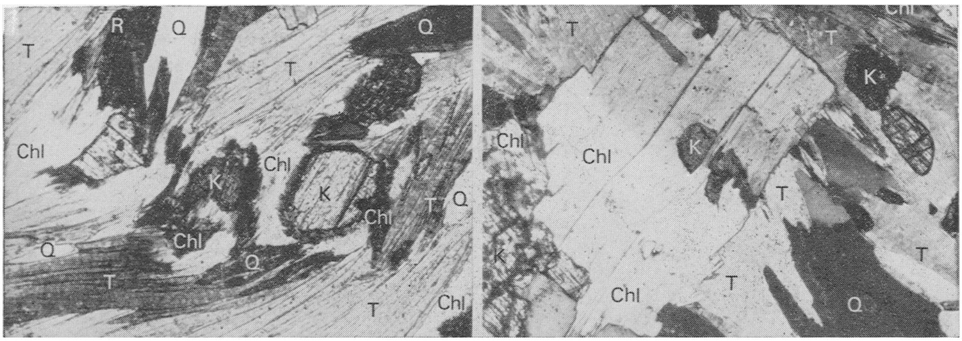
One specimen (8HC 234) of talc–kyanite–albite–quartz schist is somewhat finer-grained than the other samples, and shows distinct compositional banding. The albite (0·08–0·16 mm in size) is mostly untwinned and contains plentiful opaque dusty inclusions. The texture of the schist again indicates the contemporaneous crystallization of the main phases.

The matrix of the porphyroblastic type of talc–kyanite–quartz schist is similar to that of the non-porphyroblastic variety described above. In it are set somewhat elongated nodules, creamy-white in colour and up to 2·5 cm long, which are composed mainly of talc with relatively small proportions of quartz and irregularly shaped kyanite in the central portions. These nodules are believed to be pseudomorphs after porphyroblasts of a mineral the composition of which was probably near that of talc.

[1] Numbers refer to samples and thin-sections in the reference collection at the Geological Survey Department, Zambia.

No unaltered prophyroblasts have been recorded from these rocks. Heavy mineral concentrations of sediment samples from streams draining Chilapila Hill do not contain any likely minerals besides gedrite, which is probably derived from the kyanite-gedritites.

In various samples a considerable part of the talc and kyanite has reacted to form a finer-grained aggregate of colourless Mg-chlorite and quartz. A planimetric analysis of one sample (8HC 459) shows the presence of 19·5 vol. % of chlorite. Quartz



FIGS. 2 and 3: FIG. 2 (left). Talc-kyanite-Mg-chlorite-quartz schist (8HC 459) showing the retrogressive growth of chlorite (Chl) and quartz (Q), and kyanite (K) enclosed in talc (T). Accessory rutile and hematite are located at the upper and lower edge of the fig. respectively; oblique polars, ×37. FIG. 3 (right). Talc-kyanite-Mg-chlorite-quartz schist (8HC 459) showing cross-cutting Mg-chlorite (Chl) replacing talc (T) and enclosing relics of kyanite (K), and some quartz (Q). Rutile and hematite are accessory minerals; oblique polars, ×37.

generated during this reaction cannot always be differentiated from the early equant quartz grains of the talc-kyanite-quartz assemblage. However, in some instances, the later quartz is distinguished by a strong wavy extinction and by plentiful, minute, subparallel micaceous inclusions. Overgrowths of late quartz on grains of early quartz are occasionally quite distinct. The late chlorite and quartz are concentrated either in certain bands parallel to the pre-existing schistosity, or in the form of reaction rims around kyanite enclosed in talc (fig. 2). Large cross-cutting flakes of Mg-chlorite with inclusions of relict kyanite are occasionally seen replacing talc (fig. 3).

Mineralogy

The identification of the minerals comprising the talc-kyanite-quartz schists (and chlorite-kyanite-quartz schist) is based on their optical properties, refractive indices, and their X-ray diffraction patterns (114·6 mm diameter camera). Typical mineral assemblages are:

8HC 159 *talc*-kyanite-quartz-hematite-rutile-tourmaline
8HC 161 *talc*-kyanite-quartz-*hematite*-rutile-tourmaline
8HC 459 *talc*-Mg-chlorite-*kyanite*-quartz-*hematite*-rutile-*tourmaline*
8HC 234 *talc*-quartz-kyanite-*albite*-hematite-rutile-tourmaline-apatite
8HC 157* *talc*-kyanite-quartz-hematite-rutile-tourmaline
8HC 160* talc-kyanite-quartz-hematite-rutile-tourmaline

(The minerals shown in italics were identified by X-ray powder photographs).
* porphyroblastic talc-kyanite-quartz schist.

Planimetric analyses of thin-sections of three samples of talc–kyanite–quartz schist and four of Mg-chlorite–kyanite-quartz schist are set out in table I. In view of the homogeneous nature of the schists, the modal compositions are believed to be representative. The chlorite–kyanite schists contain less kyanite than the talc–kyanite schists since the alumina in the former is mainly in the Mg-chlorite.

TABLE I. *Planimetric analyses (in vol. %) of talc–kyanite–quartz and Mg-chlorite–kyanite–quartz schists. Point interval 0·30 mm*

	8HC 159	8HC 161	8HC 459	8HC 162*	8HC 466†	8HA 194†	8HA 195†
Quartz	35·5	47·8	21·2	45·1	36·4	27·3	34·9
Talc	43·8	30·1	43·5	2·2			
Mg-chlorite			19·5	42·8	51·2	70·8	42·4
Colourless mica				?	6·8		
Red-brown mica							5·6
Kyanite	17·5	16·9	12·8	4·1	1·5	1·2	12·5
Hematite	1·5	4·6	2·5	4·7	3·7	0·4	3·6
Rutile	1·3	0·5	0·3	0·7	0·3	0·3	0·7
Tourmaline	0·3	0·1	0·2	0·2	0·1		0·2
Apatite	0·1			0·1			0·1
?Kornerupine				0·1			
Number of points	2041	1570	1223	1848	1316	871	1409

* Downgraded Mg-chlorite–kyanite schist.
† 'Primary' Mg-chlorite–kyanite schist.

Talc in the rocks from Chilapila Hill is invariably colourless in thin section and forms relatively large crystals with a small 2V (for 8HC 159, $2V_\alpha = 8–9°$). Refractive indices were measured on four samples: 8HC 159, $\beta = 1·581$; 8HC 161, $\beta = 1·577$; 8HC 234, $\beta = 1·580$; 8HC 459, $\beta = 1·576$.[1] The X-ray diffraction patterns match closely the data of ASTM card No. 13-558. As no X-ray data have been reported for a talc crystallized in a high-pressure environment, *d*-values corrected for dilatation of the film and intensities measured from a densitometer chart are quoted for carefully handpicked talc from 8HC 159: 9·35 (100), 4·55 (70), 3·513 (25), 3·120 (95), 2·888 (10), 2·637 (10), 2·599 (35), 2·447 (65), 2·336 (10), 2·230 (20), 2·199 (25), 2·125 (25), 2·098 (15), 1·871 (16), 1·732 (10), 1·693 (17), 1·667 (22), 1·558 (9), 1·528 (50), 1·513 (16), 1·407 (21), 1·387 (20), 1·336 (5), 1·320 (10), 1·302 (16).

A partial analysis of talc concentrate from 8HC 159, containing approximately 2 % quartz and 0·6 % kyanite (as determined by grain counting), gave 0·35 % Al_2O_3 and 0·06 % total iron as Fe_2O_3. The alumina is nearly completely accounted for by the kyanite impurity, and the talc appears to be very low in alumina. Similarly, the value of $2\theta = 28·58°$ for the reflection 006 obtained for the talc indicates aluminium-free talc (Fawcet and Yoder, 1966). This contrasts with the Mautia Hill talc, which has an Al_2O_3 content of 3·95 wt. % (McKie, 1958). The low content of total

[1] All refractive index measurements quoted in this paper are ±0·003.

iron, as well as the rather low value of the refractive index β, indicate a talc composition close to the magnesium end member.

Kyanite from 8HC 459 was identified by X-ray powder diffraction and in the other samples by its optical properties in thin-section.

Mg-chlorite, derived by reaction between talc and kyanite, is white to greenish-grey in hand specimen; in thin-section it shows properties similar to those of the chlorite in the 'primary' Mg-chlorite–kyanite–quartz schists. Chlorite from a nearly completely downgraded talc–kyanite schist 8HC 162 has a small $2V_\gamma$ and $\beta = 1{\cdot}575$.

Hematite occurs in all the samples and there is probably no other iron oxide present. In the X-rayed opaque mineral concentrates obtained by hand-picking, only hematite reflections were found.

Tourmaline from 8HC 459 gave an X-ray powder pattern closely similar to that of dravite (ASTM card No. 14-76). It is weakly pleochroic with ϵ colourless and ω 1·651, very light brown-yellow. Tourmaline from 8HC 234 has a similar pleochroism, ϵ colourless, ω 1·642, very light brown. The composition of the tourmaline apparently reflects the magnesian composition of the host rock.

Kornerupine (?). A colourless accessory mineral present in a thin-section of a Mg-chlorite–kyanite–quartz schist (8HC 162) could not be definitely identified. $2V_\alpha$, measured on a nearly square-shaped cross-section, is 60° (assuming n of the mineral = 1·80). The birefringence γ–β was estimated at 0·011. Sections tilted some 30–40° about β show second order interference colours indicating γ–α approximately 0·020. An attempt to separate the mineral from a crushed sample was unsuccessful. The optical properties observed compare well with those of the kornerupine from Mautia Hill (McKie, 1965).

Cordierite, yoderite, ortho-amphiboles, and orthopyroxenes were not recorded from thin-sections or crushed concentrates of the talc–kyanite–quartz schists.

Related assemblages

Mg-chlorite–kyanite–quartz schists comprise a significant proportion of the country rocks in which the talc–kyanite assemblages occur. They are light greenish-grey in colour and strongly schistose. The textural relationship between the chlorite and kyanite is interpreted as indicating contemporaneous crystallization of the two minerals and is distinct from that of chlorite–kyanite schists of retrogressive origin. Three samples selected for planimetric analysis (table I) show the following mineral assemblages (the minerals in italics were identified by X-ray diffraction):

8HC 466 *Mg-chlorite*–kyanite–quartz–*colourless-mica*–hematite–rutile
8HA 194 Mg-chlorite–kyanite–quartz–*hematite*–rutile
8HA 195 Mg-chlorite–kyanite–quartz–red-brown-mica–hematite–rutile–tourmaline–apatite

The Mg-chlorite is colourless in thin-section, with small 2V and birefringence 0·010. For 8HC 466 and 8HC 194, $\beta = 1{\cdot}573$ and 1·572 respectively. These properties indicate a composition within the field of sheridanite or clinochlore (Deer *et al.*, 1962). Colourless mica present in 8HC 466 gave an X-ray pattern similar to that of a heated montmorillonite. The weakly pleochroic mica, bright red-brown in colour (8HA 195), was not studied in detail as only a small sample was available.

Gedrite–kyanite assemblages. Kyanite-bearing cordierite gedritites occur at some 20 localities in the Luangwa Bridge (1430 SW.) and the Chongwe river (1529 SW.) areas. These rocks typically contain quartz, often garnet, staurolite, and biotite, and rarely sillimanite, green monoclinic hornblende, and calcic plagioclase. The cordierite was formed by reactions involving gedrite, kyanite, and quartz during a later recrystallization. The resulting textures are similar to those described by Robinson and Jaffe (1969) in material from New Hampshire, U.S.A.

Although the gedrite–kyanite assemblage is now known from several localities (see quotation in Schreyer and Seifert, 1969), most occurrences described in the literature are in the form of a single outcrop. In the southern and central part of the Luangwa Bridge area there are some 14 known occurrences of cordierite–kyanite gedritites distributed over an area of 60 km by 30 km. The widespread occurrence of these rocks indicates pressure-temperature conditions of regional extent, suitable for the formation of the kyanite-gedrite assemblage. However, unlike in the Chongwe river area, there are no known occurrences of talc–kyanite–quartz assemblages in the Luangwa Bridge area. This 'Lower Basement' terrain of supracrustal polymetamorphic gneisses and quartzites was metamorphosed during an early stage in the high-temperature amphibolite facies with subsequent regional migmatization and granitization (S. Vrána, in prep.). Granulite facies assemblages, including a kyanite–orthopyroxene gedritite, which is described below, and also an orthopyroxene–sapphirine–gedrite–spinel rock, are quite rare. They are interpreted as indicating local transitions of the pre-granitization amphibolite facies metamorphism to the granulite facies, rather than relics of an earlier granulite facies metamorphism developed on a regional scale.

Orthopyroxene–kyanite assemblages. A gedrite–bronzite–cordierite–sillimanite rock (9GC 350), in which kyanite is preserved in close proximity to the orthopyroxene, occurs in the Kashindu River, Luangwa Bridge area, 30° 10′ E., 14° 46′ S. Besides dark brown-grey gedrite and bronzite the rock contains light grey elongated pseudomorphs (probably after kyanite) up to 10 cm in length, composed of cordierite, plentiful sillimanite in swarms of subparallel needles, some gedrite, and irregular or bladed grains of kyanite. Small grains of kyanite in the matrix occur in close proximity to the orthopyroxene, with gedrite forming reaction rims between the two minerals. The rock apparently experienced several crystallization stages and it is uncertain whether all the gedrite present in the matrix was formed by reaction between bronzite and kyanite, or whether some of it pre-dates the orthopyroxene.

A sample (8HD 111) from the Rufunsa area also contains both kyanite and Mg-rich orthopyroxene. The textural relationships and crystallization history of this rock are also complicated, but appear to be basically similar to that of the Kashindu River material.

Coexistence of kyanite and an orthopyroxene in natural material is quite rare. Chinner and Sweatman (1968) deduced the former existence of a kyanite–enstatite assemblage from an enstatite–cordierite–sillimanite rock occurring in a pyroxene-granulite facies environment in Rhodesia. The texture of the sillimanite–cordierite pseudomorphs after kyanite in the Kashindu River material is very similar to that described by Chinner and Sweatman, and seems to corroborate their conclusion concerning the former existence of kyanite. The Zambian kyanite–bronzite rocks probably experienced a crystallization history similar to that of the Rhodesian enstatite rock. In the latter case secondary gedrite was not formed by the reaction of enstatite and kyanite, which may reflect the very low Fe^{2+}/Mg ratio of the rock rather than unsuitable pressure–temperature conditions. Recently, the kyanite–orthopyroxene pair was described by Morse and Talley (1971) from deep-seated granulites in central Labrador, Canada.

Discussion

The assemblages described above are plotted on fig. 4, which is derived from the pressure–temperature grid of Schreyer and Seifert (1969) for the system $MgO–Al_2O_3–SiO_2–H_2O$. With a few exceptions only quartz-bearing fields are reproduced, since the

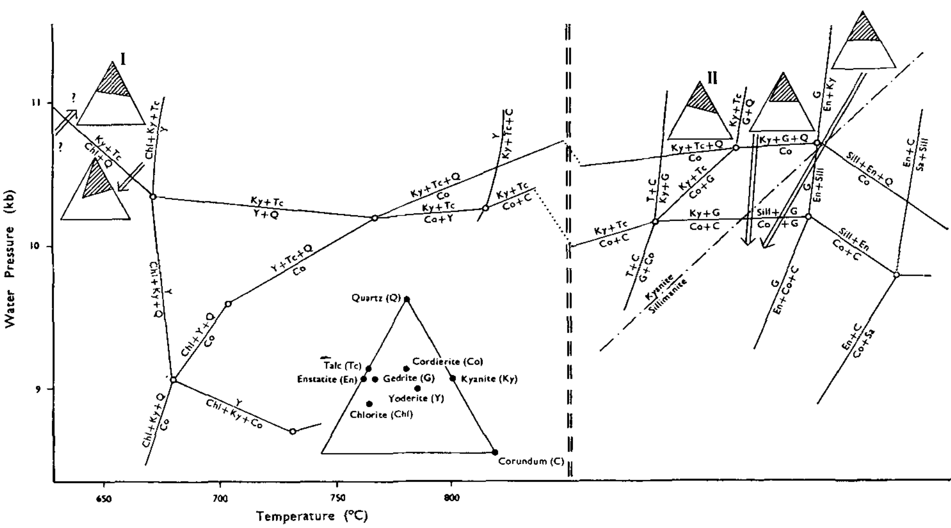


FIG. 4. Pressure–temperature grid for the system $MgO–Al_2O_3–SiO_2–H_2O$ at high pressure (after Schreyer and Seifert, 1969). The diagram is a combination of figs. 1 and 2 in the paper quoted. The higher-temperature part of the diagram to the right of the double-dashed line shows relative positions of the invariant points only. Iron content of gedrite and orthopyroxene and possible aluminium content of orthopyroxene are ignored. The talc–kyanite–quartz assemblage is plotted in two positions (I and II) to indicate the range of temperature under which the assemblage could crystallize at pressures close to the lower-pressure boundary of its stability field. The double-line arrows show which univariant curves were transgressed during subsequent retrogressive reactions. They are not intended, however, to indicate continuous paths in change of P–T conditions.

assemblages in all the new occurrences contain quartz. The diagram indicates that the lower-pressure boundaries of the stability fields of the assemblages talc–kyanite–quartz, gedrite–kyanite–quartz, and enstatite–kyanite–quartz all lie marginally above 10 kb, which corresponds to depths of about 35 km, that is depths close to the continental Moho.

The presence of albite in the talc–kyanite–albite quartz schist sets an upper pressure limit on the conditions under which this assemblage was formed. According to Birch and LeComte (1960), the univariant curve for the reaction albite→jadeite+quartz is at 200–300 °C for pressures of approximately 10 kb. These temperatures are, however, too low for the assemblage talc–kyanite to crystallize near the low-pressure boundary of its stability field (Schreyer and Seifert, 1969). At more realistic temperatures in the range 500 to 700 °C, the curve is at about 17·5–20 kb. The pressure at which the above assemblage crystallized therefore lies in the range of 10 to 20 kb.

Though chemical analysis of the individual rock types are not available at present, with the exception of two samples of cordierite–kyanite gedritite from the Luangwa Bridge area, it is possible to show that, besides pressure and temperature, oxygen fugacity is an important factor for the stability relations of the assemblages. The kyanite-bearing assemblages fall into two distinct groups: hematite-bearing talc–kyanite schists and Mg-chlorite–kyanite schists with a relatively high Fe^{3+}/Fe^{2+} ratio, and hematite-free gedritites, including the bronzite–kyanite gedritites, with a relatively low Fe^{3+}/Fe^{2+} ratio.

Ilmenite, sometimes accompanied by staurolite, in some of the gedritites can be shown on textural evidence to have formed during the later reaction, gedrite+kyanite+quartz → cordierite+H_2O, to accommodate the surplus iron released.

The talc–yoderite–kyanite–quartz schist from Mautia Hill may show a change of Fe^{3+}/Fe^{2+} ratio during its evolution. The early (pre-yoderite) assemblage talc–kyanite–quartz contained hematite as an essential iron-bearing phase while the purple yoderite that formed subsequently has an Fe^{3+}/Fe^{2+} ratio of 0·04/0·45 (McKie, 1959). For a green variety of yoderite from the same locality McKie and Bradshaw (1966) obtained an essentially higher ratio of 0·32/0·16. In view of the difficulty in determining the ferrous/ferric ratio in yoderite, the oxidation ratio is not known exactly at present. However, if the iron in yoderite is not entirely ferric, a decrease in oxygen pressure would favour its crystallization relative to the assemblage talc–kyanite–hematite–quartz. In the Zambian talc–kyanite–quartz schists the oxygen pressure was probably maintained at a high level during downgrading since no mineral containing significant ferrous iron was formed.

Talc–kyanite–quartz schists and kyanite gedritite, in part downgraded to Mg-chlorite–kyanite–quartz schist and a cordierite-bearing assemblage respectively, are closely associated at two localities in the Chongwe River area. The textural evidence indicates that the downgrading can be bracketed in time between two fold phases. The replacement of high- by low-pressure assemblages in two closely associated rocks suggests that the reactions were contemporaneous, even though the resulting assemblages differ very significantly. Evidence for the successive development of the schist and gedritite assemblages is scanty. The texture of the majority of the talc–kyanite–quartz schists indicates a single phase of recrystallization. The porphyroblastic schist, however, probably has a more complex history involving: growth of talc, kyanite, quartz, and hematite in the matrix; growth of the porphyroblastic mineral, presumably rich in magnesium; and complete replacement of the porphyroblasts by talc and subordinate quartz.

With the information at present available, the firm correlation of the recrystallization stages of the porphyroblastic talc schist with the primary and retrograde assemblages of the talc–kyanite schists and kyanite gedritites is not possible.

There is plentiful evidence for high-pressure metamorphic recrystallization at comparatively low temperatures corresponding to the jadeite–glaucophane type of metamorphism, as well as at high and very high temperatures corresponding to the eclogite facies and kyanite granulites (Turner, 1968). In contrast, mineral assemblages diagnostic of high-pressure regional metamorphism at moderate temperatures corresponding to the amphibolite facies have seldom been described. This is due in part to the continued stability of plagioclase up to pressures in excess of 15 kb at these temperatures, which probably precludes its breakdown to higher-pressure minerals in crustal rocks. Kyanite, although frequently present in amphibolite facies rocks, is of limited value as an indicator of high pressures since recent work on the aluminium silicate triple point indicates that kyanite can form at pressures as low as 2–3 kb (Turner, 1968). The diagnostic high-pressure assemblages at amphibolite facies temperatures are restricted to aluminous rocks with unusually low Fe^{2+}/Mg ratio. The talc– and Mg-chlorite–kyanite–quartz schists and the kyanite gedritites of the Chongwe River area are associated with basic metavolcanic rocks and underlying schists, typically showing the assemblages quartz–andesine–hornblende–epidote–iron-ores, and quartz–oligoclase-andesine–biotite ($\pm$hornblende–epidote–garnet) respectively. The evidence at present available indicates that these assemblages are contemporaneous with those of the magnesium–aluminium-rich rocks, and are distinguished from later assemblages by an important fold phase represented throughout the area by a strain-slip cleavage. No disequilibrium textures that can be correlated with the alteration of the primary to the retrograde assemblages of the talc–kyanite–quartz schists and kyanite gedritites have been recorded. Further examination of the basic metavolcanics and underlying schists, in particular the composition of individual phases, may reveal significant divergences from typical amphibolite-facies mineralogy. However, a tentative conclusion, that these assemblages are typical of the amphibolite facies while having crystallized at pressures in excess of 10 kb seems justified.

Acknowledgement. The authors would like to thank Dr. G. A. Chinner for commenting on the manuscript and for drawing our attention to the kyanite-talc assemblage in the Allalin meta-gabbro.

Addendum

Preliminary microscopic work on samples collected during reconnaissance regional mapping of the North-Western Province of Zambia indicates that talc–kyanite–quartz schists are an abundant rock-type of the lower part of the Katanga sequence of that area. Some fifty samples from the Solwezi area (mapped by J. W. Arthurs), and the country around Mwinilunga (mapping in progress by J. D. Appleton and B. A. Klinck) contain this assemblage. The associated rocks include phlogopite–kyanite–quartz schists and retrograde Mg-chlorite-rich schists. It may be that talc–kyanite–quartz schist is not as rare a rock-type as the paucity of reported natural occurrences suggests. There is a possibility that some of the rocks described elsewhere as muscovite–kyanite schist may, in fact, contain the assemblage talc–kyanite.

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