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# Kyanite Pseudomorphs after Andalusite in Polymetamorphic Rocks of the Sierra Nevada (Betic Cordillera, Southern Spain)

By *E. Puga* (Granada) *), *J. M. Fontboté* (Granada) *), and *J. L. Martín-Vivaldi* (Madrid) **)

With 10 figures and 1 table in the text

**Abstract**

Some of the rocks of the Caldera-Unit belonging to the Sierra Nevada Complex provide specially interesting information on its metamorphic history. They are micaschists whose aspect resembles somewhat that of hornfelses. They contain conspicuous prisms of kyanite pseudomorphs after andalusite (chiastolite). The kyanite is more or less altered to sericite.

Numerous minerals have been identified in the micaschists' matrix: quartz, garnet, staurolite, chloritoid, biotite, muscovite, paragonite, chlorite, and graphite. They belong to distinct successive parageneses developed in different stages of the metamorphic history of the rock. Garnet nodules originating from old biotite are particularly interesting.

Thermodynamic and geological conditions responsible for the pseudomorphic transformation andalusite-kyanite, as well as for the different successive parageneses, are discussed. It appears that these micaschists are truly derived from old chiastolite hornfelses. Several stages of regional alpine metamorphism have been distinguished. Two of them were clearly synkinematic and were followed by other static ones.

**Résumé**

Quelques-unes des roches appartenant à l'Unité de la Caldera (Complexe de la Sierra Nevada) fournissent des données spécialement intéressantes en rapport avec le developpement de leur métamorphisme. Ce sont surtout des micaschistes dont l'aspect évoque celui des cornéennes. Ces roches contiennent des baguettes prismatiques très apparentes qui sont constituées par du disthène pseudomorphisant de l'andalousite (chiastolite). Le disthène est plus ou moins séricitisé.

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Dans la matrice de ces micaschistes des minéraux nombreux ont été identifiés: quartz, grenat, staurotide, chloritoïde, biotite, muscovite, paragonite, chlorite et graphite. Ces minéraux appartiennent à plusieurs paragenèses successives qui se sont formées au cours de différents stades de l'histoire métamorphique de ces matériaux. Il faut notamment signaler l'existence de nodules de grenat formés aux dépens d'anciennes biotites.

Les conditions thermodynamiques et géologiques responsables du remplacement pseudomorphique de l'andalousite par du disthène sont discutées, de même que celles qui ont déterminé les paragenèses successives. Il semble que ces micaschistes proviennent de la transformation d'anciennes cornéennes. Plusieurs stades du métamorphisme régional alpin ont pu être définis et caractérisés. Deux de ces stades auraient un caractère syncinématique très net et auraient été suivis par d'autres épisodes à caractère statique.

## INTRODUCTION

In the course of field work by one of the authors (E. Puga) in the Sierra Nevada high crest, a special variety of micaschists was found. These contain conspicuously large prisms, whose features recall those of andalusite. Some of them also show the typical dark cross of chiastolite. The micaschists containing these prisms belong to the Caldera-Unit defined by Puga (1971). They occur extensively in the slopes of the Loma del Mulhacen.

Laboratory work has now revealed that the prisms are in fact constituted of aggregates of small fibrous kyanite crystals: a pseudomorphic replacement has therefore clearly taken place, and we have tried to relate this process with the metamorphic history of the region.

## PETROLOGY

These micaschists appear as dense, compact rocks whose aspect recalls that of hornfelses. Metagranites have been described in the Caldera-Unit (Puga, 1970). They could be related to these hornfels-like rocks. However, a direct contact has nowhere been found, possibly as a consequence of tectonisation.

The kyanite pseudomorphs are very conspicuous (Fig. 1). Owing to their size and whitish colour they contrast clearly with the fine-grained and dark grey groundmass, in which only some garnet phenoblasts (1–3 mm) can be identified with the naked eye.

Abundant nodules can also be distinguished, but their composition is only identifiable microscopically and will be described later. They are brownish and thus contrast with the dark grey or black groundmass. Less common are hypidiomorphic staurolite (up to 1 cm) porphyroblasts.

Microscopically the groundmass is formed by the following minerals (listed

Fig. 1. Chiastolite porphyroblasts pseudomorphically replaced by kyanite in a kyanite and garnet nodules-bearing mica-schist.

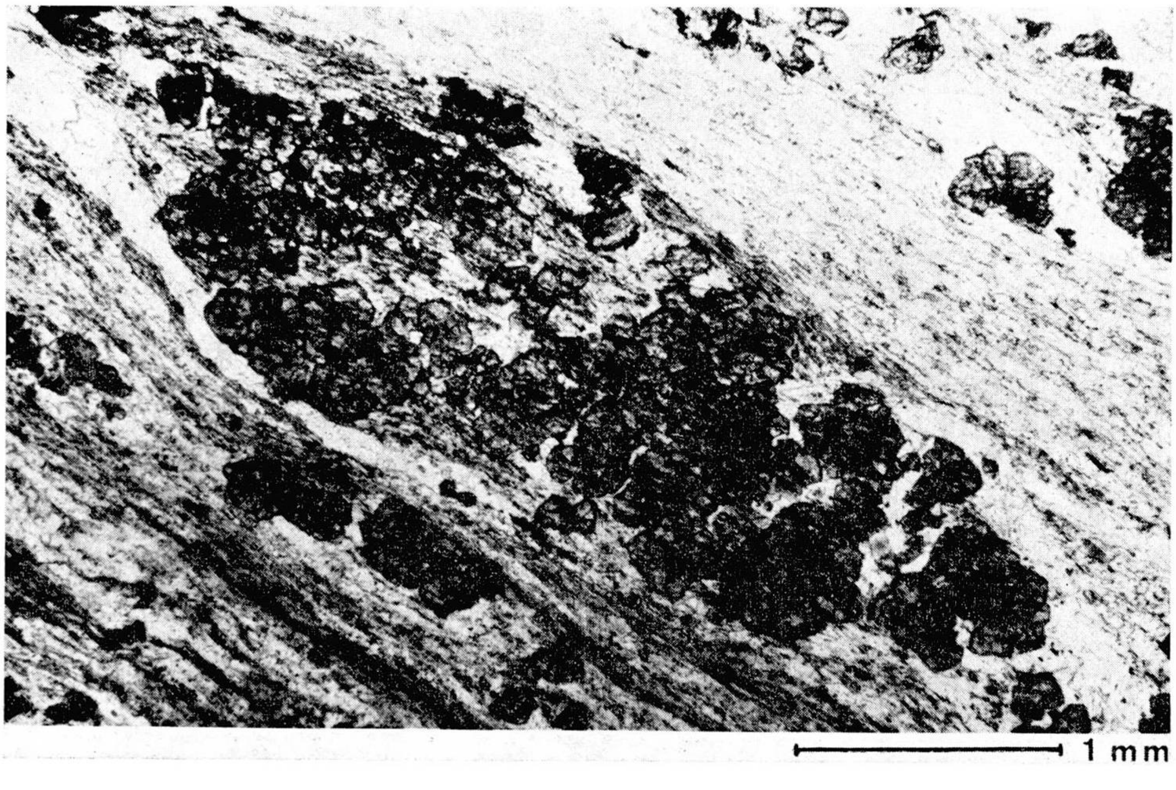


Fig. 2. Nodular aggregate of garnet. The subparallel bands of graphite dust show a former $S_1$ plane. The cleavage $S_2$ arranged around the nodule is partially coincident with $S_1$. Polarizer only.

from the most to the least abundant) white mica, quartz, garnet, graphite, staurolite, chloritoid and occasional chlorite as well as iron oxides.

The above-mentioned nodules are equally distributed throughout the rock. They appear to be made up essentially of small garnet grains with minor amounts of biotite and/or white mica. In some cases, a few quartz and/or chloritoid, and (more rarely) tourmaline crystals are present among the mica flakes. The nodules exhibit an elongated, ovoid shape. Their length is generally between 2 and 6 mm and their width between 1 and 3 mm. Their elongation is not parallel to the lineation, but remains generally in the main cleavage surfaces.

In some parts of the rock the groundmass is poorer in mica. This mica is dispersed and isolated among the quartz grains. On the other hand, in the nodules the mica is concentrated with the garnet. This suggests that neither the garnet nor the mica are fortuitously concentrated in the parts of the rock which constitute the nodules, but that they must have a common origin. They were probably formed from the same pre-existing mineral. These conditions would explain their mutual grouping and their preferential concentration in the nodules.

Dusty graphite, found within these nodules, forms abundant inclusions in

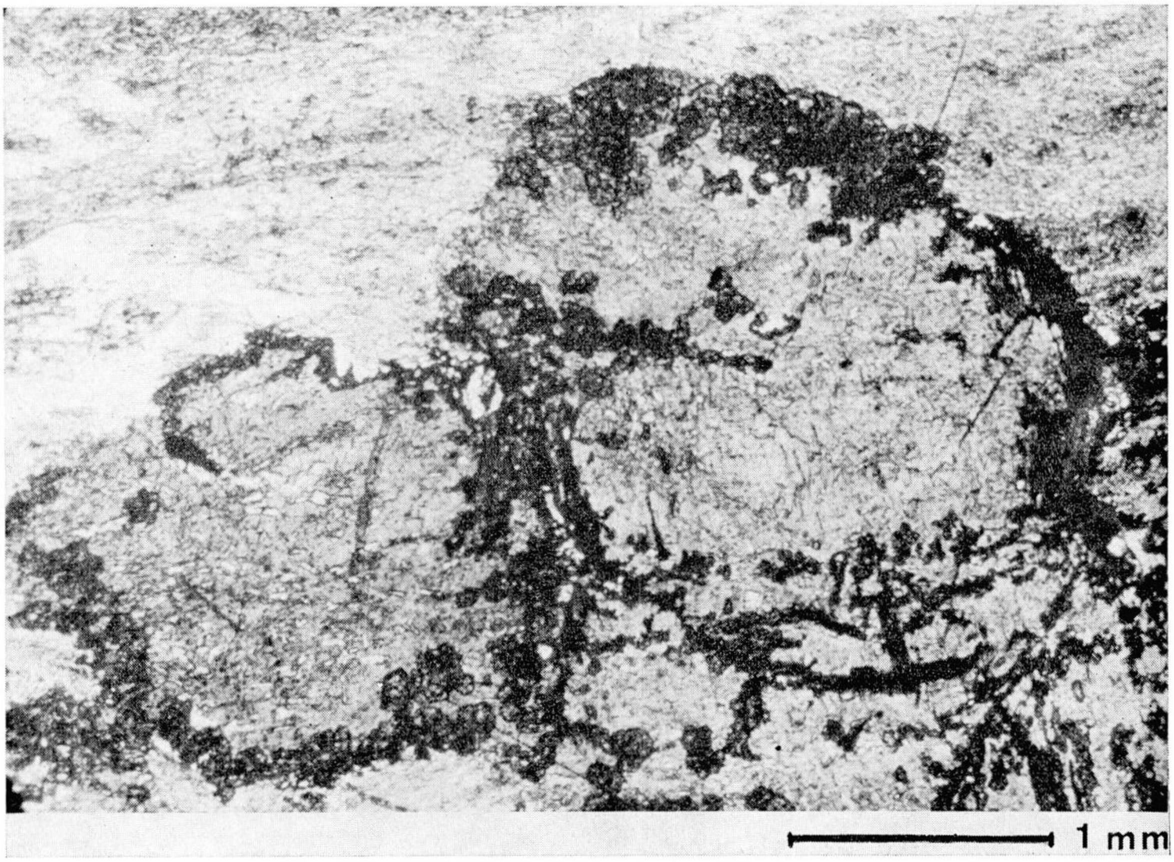


Fig. 3. Biotite porphyroblasts partially replaced by an aggregate of small garnet grains. This pseudomorphism begins on the border of the porphyroblasts and along their cracks. Polarizer only.

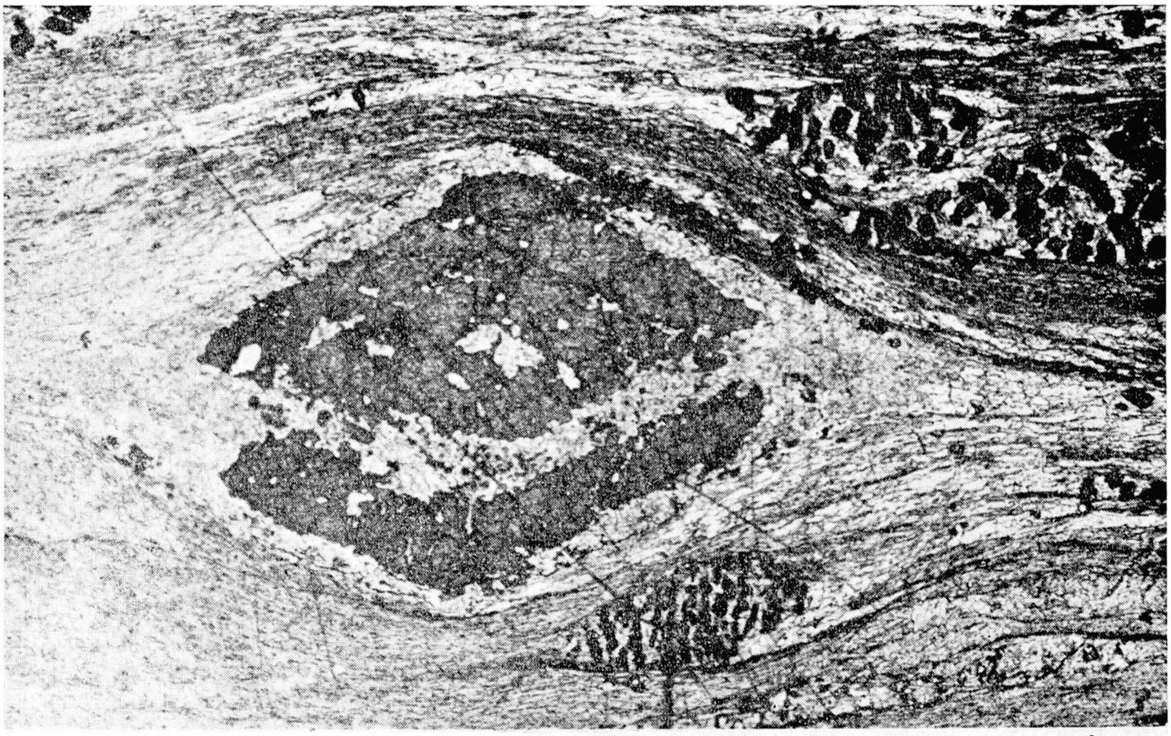


Fig. 4. Garnet nodules and a staurolite porphyroblast with overgrowth surrounded by the $S_2$. The latter is partially sericiticed not only on the border but also at the boundary between the core and the outside overgrowth rim. Crossed polarizers.

the interior of the garnets as well as between mica flakes. These inclusions show regular subparallel orientation in each nodule, as do all constituent minerals, but the orientations are different from one nodule to another, and oblique to the conspicuous schistosity of the rock (Fig. 2). The nodules are more or less deformed; some of them are flattened and tend to be parallel to the schistosity (Fig. 2). This disposition of the graphite suggests that the nodules, at present polymineralic, consisted formerly of one single mineral. This mineral had an amygdaloid or prismatic shape and already contained graphite inclusions oriented in the some way.

Numerous small garnet grains are included in the border of the nodules. Some flaws across the biotite crystals are also filled with similar garnet grains (Fig. 3). Garnet thus clearly appears to be formed from biotite. The garnet crystals as well as the remaining biotite include graphite patches. Some diversely oriented flakes of white mica surround the biotite. The orientation of the biotite crystals is also different to that of the main cleavage.

Most nodules have lost all or almost all of the old biotite, whose former existence is, however, attested by transitional stages of replacement. The biotite is thought to be paragenetic with the andalusite. It is to be remembered that the old paragenesis has been replaced by other minerals such as kyanite, garnet, white mica, etc.

Garnet apparently formed from biotite. The replacement indicates an adaptation to new metamorphic conditions related to higher pressure. After the formation of the second paragenesis another change of conditions again transformed the rock, this time under greater stress. Thus the garnet-mica clusters were deformed. The shape of their sections, at first prismatic, became amygdaloid. The nodules, in some places intensively flattened among the micaceous streaks, are finally fractured and subdivided.

Staurolite forms idiomorphic crystals. They are more or less transformed into other minerals, and generally have an external rim consisting of sericite and ore. Less commonly, chloritoid, garnet, kyanite and chlorite have resulted from staurolite alteration (Fig. 4). The optic characteristics of this staurolite have already been defined (Puga, 1971).

Garnet is visible to the naked eye. In the slides, garnet sections are hypidiomorphic and limpid. Their lack of inclusions and size make them distinguishable from the two other previously mentioned types of garnet, i.e. the nodule-forming one and that resulting from staurolite alteration (Fig. 5). Microscopically, this garnet is pale pink; it is slightly altered iron oxide along edges and fissures. X-ray diffractograms indicate that this garnet is almandine. Some grains are zoned; their core shows the features already described, while their external zone is xenomorphic, with numerous inclusions (Fig. 6).

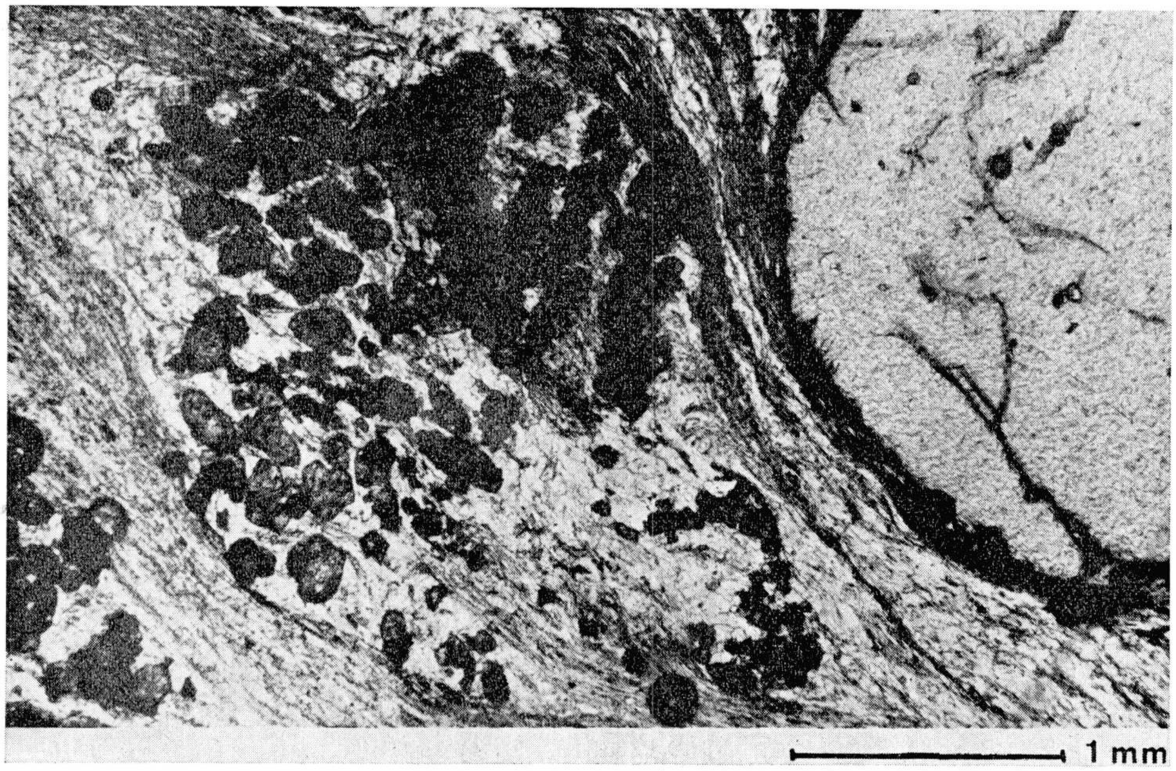


Fig. 5. Garnet nodules containing graphite inclusions. Part of an almandine porphyroblast without inclusions; slight replacement by hematite along the border. Polarizer only.

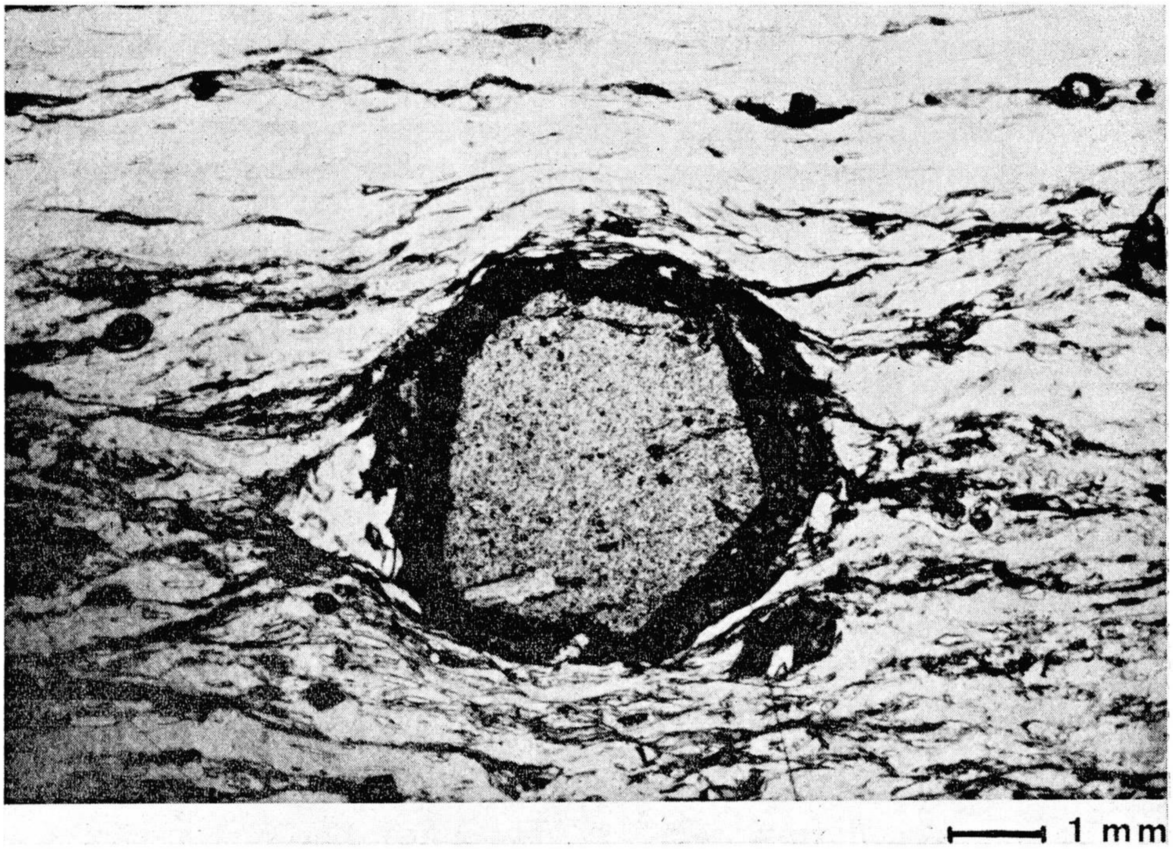


Fig. 6. Zoned garnet porphyroblast. It shows a hypidiomorphic core without inclusions and a poikiloblastic rim containing abundant graphite. Polarizer only.

Chloritoid is specially concentrated with staurolite crystals as well as with some kyanite pseudomorphs. Minor amounts of chloritoid lacking any preferred orientation appear also within the mica streaks of the groundmass. The latter may contain a few biotite flakes in some places, but biotite is subordinate to white mica. This biotite appears locally to be the product of transformation of a pre-existing chlorite.

Some flakes of white mica appear in the border zone (previously transformed into sericite) of certain pseudomorphs of the old chiastolite. The size of these flakes is on the whole larger than that of the sericite of the same pseudomorphs or that of the groundmass mica. As well as the lack of orientation of those flakes, this difference in size makes them easy to distinguish from the latter.

Chlorite is relatively scarce. It forms small crystals which are found together with the chloritoid in the staurolite alteration zones or with the garnet phenoblasts, completing the nodules between the micaceous layers of the groundmass, i.e. in the "pressure shadows" of the porphyroblasts.

## MINERALOGY OF THE PSEUDOMORPHS

As we have already mentioned, some pseudomorphs have preserved, more or less perfectly, their original prismatic forms. However, most of them appear to have been deformed. In these cases, their sections commonly show "augen" shapes.

In the sections which are normal to the main elongation and especially in the more regular prismatic grains, the chiastolite cross appears clearly. It consists of graphitic inclusions (Fig. 7, 8). Similar inclusions also occur in the irregularly shaped grains but they have lost their cruciform disposition and have become irregularly distributed.

Pseudomorphs are generally from 4 to 30 cm long, the average length being about 7 cm (Fig. 1). Transversal sections in the more regular prisms are practically square. The lengths of the sides are between 0.5 and 2.5 cm, more frequently between 1 and 1.5 cm (Fig. 7, 8). The more irregular individuals have sections of varies shapes, some of which show amoeboid forms. But in all cases the areas of transversal sections are roughly equivalent to those

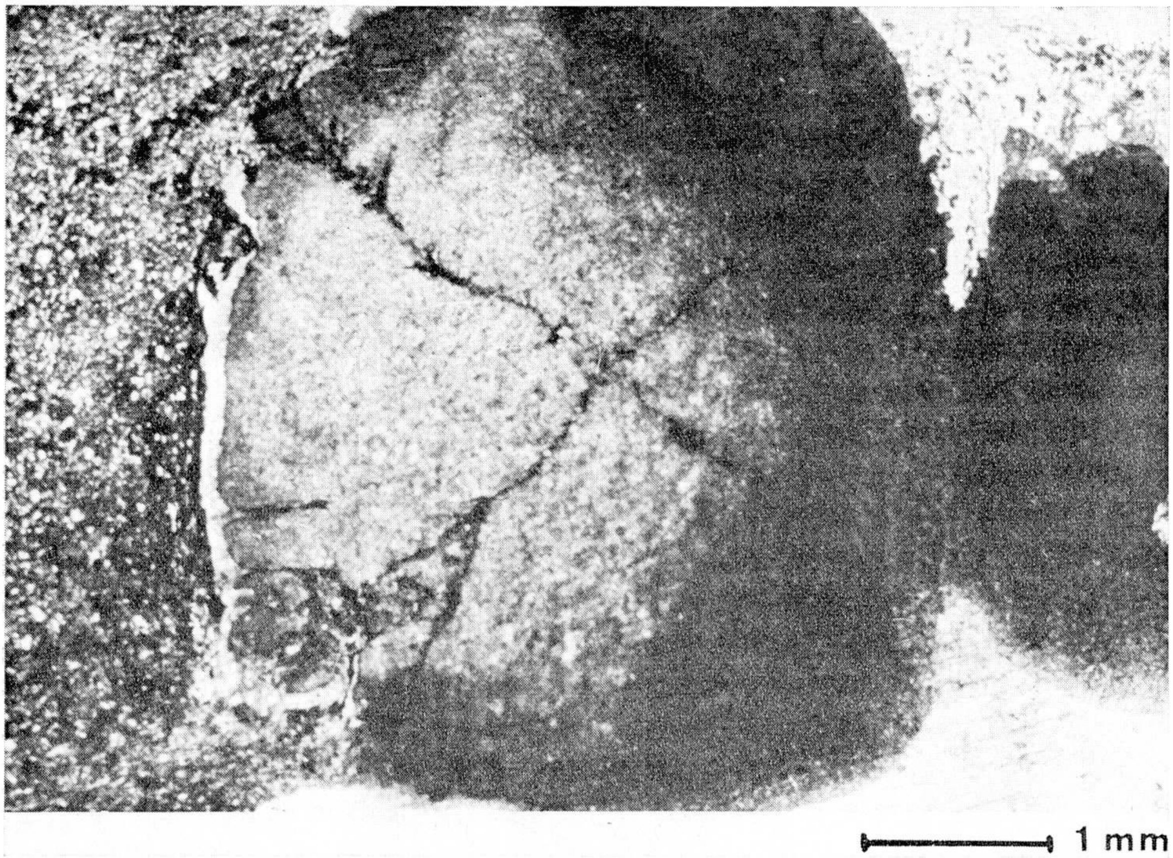


Fig. 7. Transversal section of a former chiastolite porphyroblast pseudomorphozed by kyanite. The cross pattern of the chiastolite graphite inclusions has been preserved in the core of the aggregate made up of small kyanite crystals. Polarizer only.

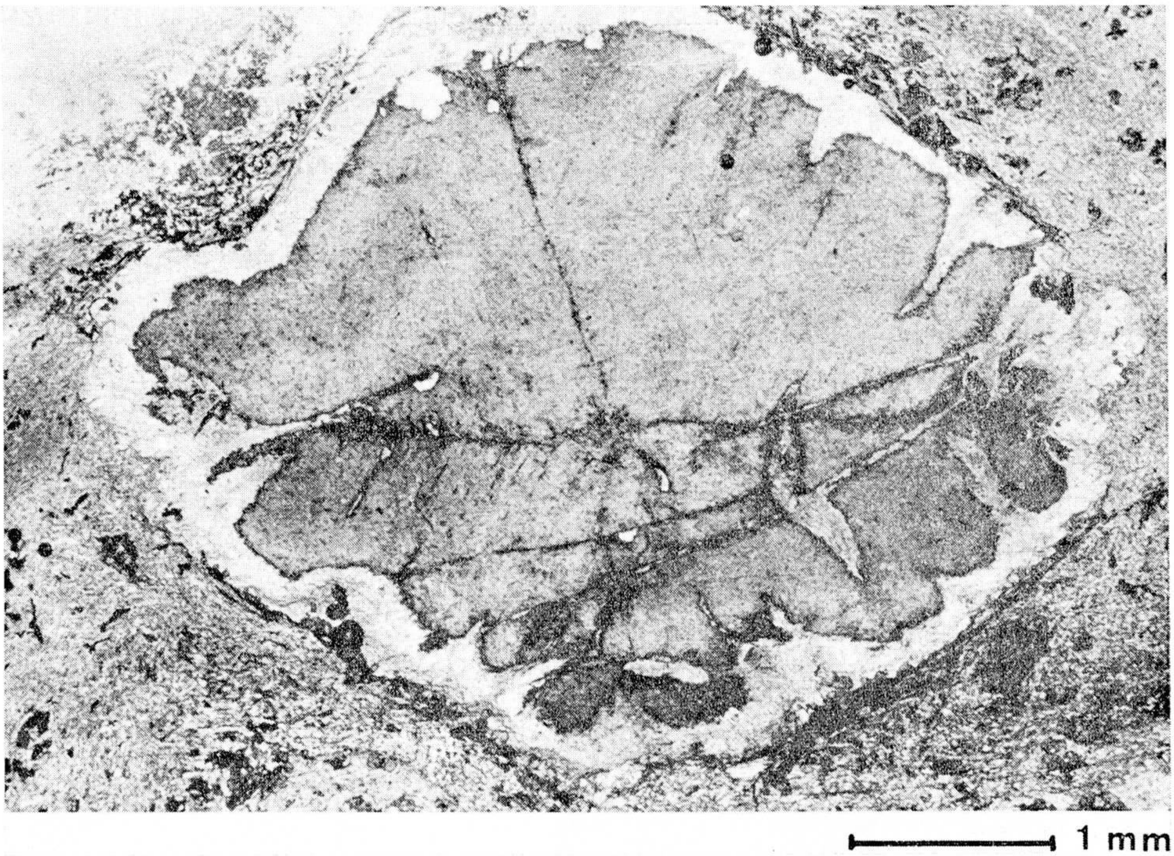


Fig. 8. Cross-section of a former chiastolite porphyroblast, pseudomorphozed by kyanite. The latter has been partially sericitized along the border. Polarizer only.

of regularly shaped sections (Fig. 9, 10). The shape of the undeformed regular individuals, as well as the existence of cross-shaped distributions in graphite inclusions, is quite typical of chiastolite.

Microscopically, each of these sections appears to be formed not by a single crystal but by a heterogeneous crystalline aggregate. In fact, several mineral types can be recognized in them:

a) Needle-shaped crystals whose optic constants are only partially elucidated. They correspond to a kyanite whose optic $2\,V_X$ angle varies between 81 and 84°; $Z \wedge c = 27$–$28°$. In many cases the size of these crystals (0.1 mm) is too small, and the determination of optic constants becomes impossible. The identification of this mineral has been made only by the study of powder diagrams, obtained from isolated porphyroblasts and also from thin sections.

These diffraction diagrams reveal that kyanite is the main constituent of porphyroblasts.

b) Sericite is also present in the pseudomorphs. X-Ray diffractograms have shown that it consists of muscovite associated with paragonite.

Besides these two main components, the porphyroblasts contain dusty graphite as well as a few twinned crystals of chloritoid lacking preferred orientation.

The relative amounts of kyanite and sericite vary according to different porphyroblasts; the degree of deformation of the latter increases as the sericite content increases. This mineral forms the peripheral part of the porphyroblasts and fills the cracks present in several cores (Fig. 8, 9). Some porphyroblasts are almost entirely formed of sericite and the kyanite may be restricted to some little isolated patches inside them (Fig. 10). Some porphyroblasts show a partial transformation of the sericite into large muscovite flakes. They lack preferred orientation and are found in the outer area of the sericitized zones.

Kyanite crystals are grouped in little bundles. They are not wholly ordered within the porphyroblasts but may show a certain degree of preferred orientation. In the longitudinal sections of porphyroblasts, most of the kyanite crystals have their c-axis parallel with that of the old chiastolite.

The inclusions may be either perfectly arranged after the typical chiastolite cross (Fig. 7, 8), or unoriented (Fig. 10). But in all cases, abundant graphitic inclusions are more linked with kyanite than with sericite.

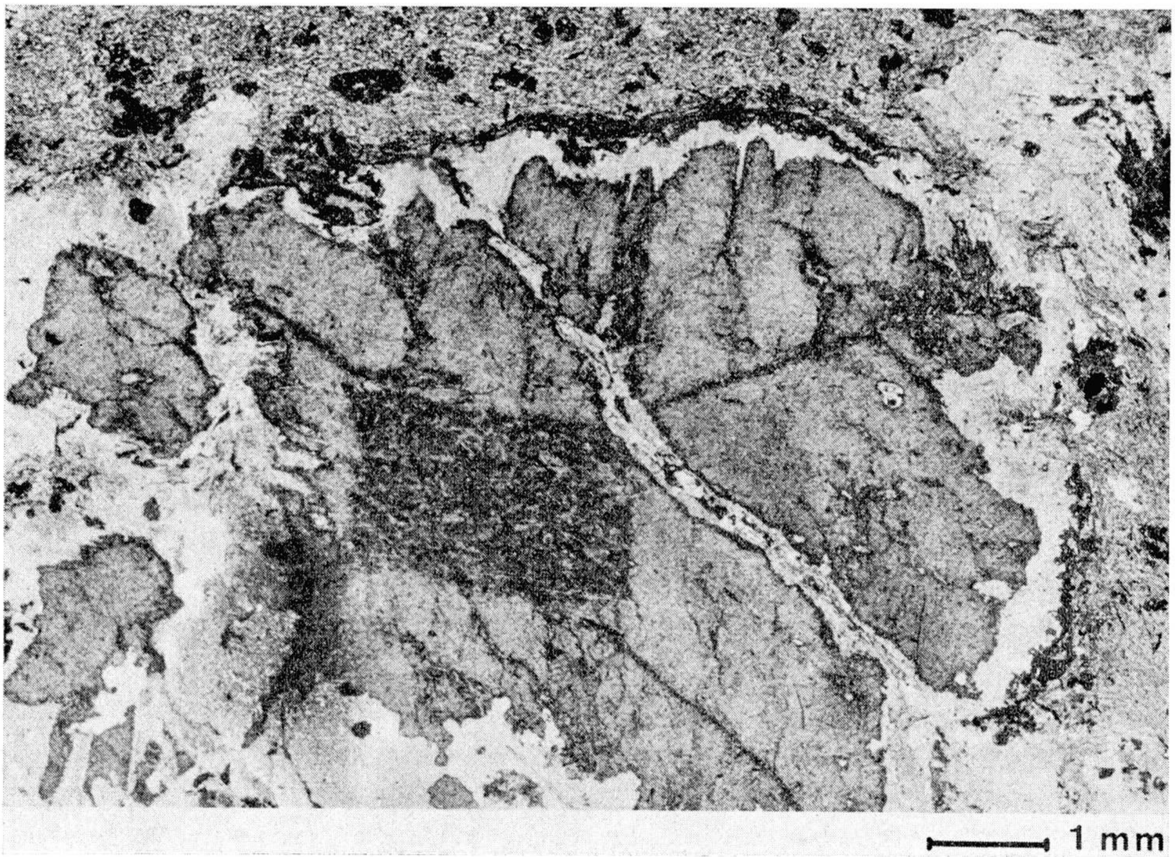


Fig. 9. Kyanite pseudomorph after chiastolite. Cross-shaped arrangement of the graphite inclusions with a rectangular accumulation in the core. The sericite has developed on the border and along cracks. Polarizer only.


Fig. 10. Cross-section of a kyanite-pseudomorph, showing intense deformation. The graphite inclusions are scattered and do not maintain the former cruciform pattern. The sericitisation has been well developed from the border. Polarizer only.

Apart from these inclusions, the old chiastolite crystals have been completely, or almost completely replaced by kyanite and sericite in variable proportions. Other possible components are chloritoid, and/or muscovite.

The external form and the persistence of the graphitic cross clearly indicate that both kyanite and sericite are pseudomorphic after chiastolite. Now, since kyanite and sericite correspond to a different metamorphic facies and their relative relationships show yet another replacement, they are not at all paragenetic (Fig. 8–10). The same arguments suggest that the chloritoid and muscovite contained in some pseudomorphs belong to different parageneses.

Thus, the following succession may be inferred:

andalusite-kyanite-sericite-muscovite-chloritoid.

Of the second and third minerals, those remaining are the crystal aggregates which have already been described.

After studying the slides it is clear that not all the minerals are paragenetic. The transformation sequence andalusite-kyanite-sericite has just been discussed as well as the further genesis of chloritoid and muscovite in some pseudomorphs.

## PETROGENESIS

From the foregoing data and statements, different successive mineral parageneses may be distinguished in these rocks and several deformation phases which affected them may be inferred. These conclusions are briefly expounded in the accompanying table "mineralogenetic and deformation stages". A summary of this table is given below.

The first stage of metamorphism recorded in these rocks is thermal metamorphism. It developed earlier than regional Alpine metamorphism, though currently available data do not permit us to ascertain further precisions about the age of this thermal metamorphism.

Structural, textural and mineralogical information leads us to consider this thermal stage as one of contact metamorphism. These rocks have in fact an appearance which is strongly reminiscent of hornfelses; i.e. absence of fissility, great density, very fine groundmass and a great development of porphyroblasts, their lack of orientation, etc. In spite of intense deformation, this aspect persists and contrasts strongly with other rocks of the Sierra Nevada. Likewise, the porphyroblasts, which we include in this stage because they are apparently paragenetic, are common to and some are even typical of contact metamorphism.

Minerals formed during this first metamorphic stage (chiastolite, biotite, staurolite, almandine ...) have been affected by a regional dynamothermic polyphasic and plurifacial metamorphism. Alpine metamorphism produced a series of successive parageneses, a second stage of transformation, as indicated in table 1.

The regional Alpine metamorphism of these rocks comprises several "mineralogenetic phases" which alternate with dynamic or deformation phases as witnessed by successive mineral parageneses and textural features.

During the successive mineralogenetic phases the minerals of the former ones were partially transformed into each other. A detailed microscopic study allows us to group these minerals in different parageneses based on their interrelationships. Each of these parageneses belongs to a different thermodynamic condition, more or less accurately defined by their respective facies. From textural characteristics as well (mentioned in the petrology section), we have classified these phases as "synkinematic" "postkinematic" or "late synkinematic" (see table 1).

This Alpine metamorphism has not given rise to high pressure mineral assemblages in these rocks. The parageneses indicate rather middle pressure metamorphism. This is probably due to the chemical composition of the rock more than to the geothermal gradients of this metamorphism. This may be

Table 1. *Mineralogenetic and deformation stages.*

| 1st Stage: *Prealpine thermal metamorphism* | 2nd Stage: *Alpine, regional, dynamothermal metamorphism* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hornblende-hornfels facies | Phase I: Glauco-phanitic Greenschist facies | 1st dyna-mic phase | Phase II: Postkinematic Greenschist facies | 2nd dynamic phase | Phase III: Late synkinematic Greenschist facies | Phase IV: Postkinematic Almandine-amphibolite facies | 3rd dynamic phase | Phase V: Post-kinematic Greenschist facies |
| 1 Quartz, white mica, biotite, gra-phite, tourmaline | 1 w. ch.* | Fractures, splitting | 1 w. ch. | Microfolding of matrix and of the partially sericitized kyanite pseu-domorphs | 1 w. ch. | 1 w. ch. | "Flat-tening" | 1 w. ch. |
| 2 Chiastolite | 2 Kyanite (pseudo-morphs) | | 2 Sericite | | 2 w. ch. | 2 Paragonite and muscovite | | 2 Chloritoid |
| 3 Biotite | 3 Garnet II (as nodules) | | 3 w. ch.<br>3′ Sericite | | 3 w. ch.<br>3′ w. ch. | 3 w. ch.<br>3′ w. ch. | | 3 w. ch.<br>3′ w. ch.<br>3″ Chloritoid |
| 4 Staurolite | 4 w. ch.<br>4′ Kyanite | | 4 Sericite and ore<br>4′ w. ch. | | 4 w. ch.<br>4′ w. ch. | 4 Garnet III<br>4′ w. ch.<br>4″ Paragonite and muscovite | | 4 w. ch.<br>4′ w. ch.<br>4″ Chlo-ritoid<br>4‴ Chlorite II |
| 5 Almandine | 5 w. ch.<br>5′ Garnet II (over-growth) | | 5 w. ch.<br>5′ w. ch. | | 5 w. ch.<br>5′ w. ch. | 5 w. ch.<br>5′ w. ch. | | 5 Hematite<br>5′ Hematite |
| | | | | | 6 Chlorite I (pressure shadows) | 6 Biotite | | 6 w. ch. |
| | | | | | | | | 7 Chlorite II |

* w. ch. = without change.

deduced from the petrological context in which these rocks are found, as they are associated with others bearing glaucophane or jadeite with quartz.

Table 1 also shows the variation with time of the thermodynamic conditions of the metamorphic phases.

During the first Alpine phase the big porphyroblasts of chiastolite due to contact metamorphism were pseudomorphosed and completely transformed into kyanite aggregates. Likewise, the biotite porphyroblasts were partially pseudomorphosed by nodular aggregates of garnet. These pseudomorphic processes were developed, partially at least, without any deformation of the porphyroblasts, so that locally the original pattern of the graphite inclusions (cross-like for the chiastolite, subparallel for the biotite) has been preserved. The porphyroblasts of staurolite were barely transformed in this phase; only some isolated crystals of kyanite developed at their expense. Finally, the almandine which accompanied the early porphyroblasts remained stable in the first phase of Alpine metamorphism, during which they were preserved and even locally acquired overgrowths.

The first dynamic phase, which followed the first mineralogenetic phase, is essentially characterized by fracturing followed by splitting of the porphyroblasts of staurolite and of the kyanite aggregates.

Mineralogenetic phase II was postkynematic. The circulation of fluids brought about retrometamorphism and hydrated minerals were formed, e.g. abundant sericite from the pre-existent kyanite and staurolite. The development of sericite from the residual biotite between some garnet nodules probably belongs to this phase.

A very severe second dynamic phase followed. During this phase the groundmass was microfolded. Kyanite and sericite replacing the old chiastolite porphyroblasts were microfolded too.

During the third synkinematic phase, chlorite was developed in "shadow zones" of the pre-existing porphyroblasts.

Phase IV was postkinematic, if produced minerals which indicate a temperature increase with respect to that of phases II and III.

In effect, relatively large muscovite and paragonite crystals were formed at the expense of the sericite derived from the retrometamorphism of kyanite. Small crystals of garnet also formed from sericite and ore aggregates from staurolite. Finally, chlorite was partially transformed into biotite.

After this mineralogenetic phase, general flattening of the rock took place. We consider this event as belonging to the third dynamic phase. Flattening resulted from a stretching of the groundmass minerals, which were in this way partly adapted to the external shape of the porphyroblasts.

The fifth mineralogenetic phase was postkinematic as well; it is characterized by the relatively plentiful development of small chloritoid and chlorite crystals from the white mica, sericite and kyanite forming the porphyroblasts. In this phase garnet was slightly retrometamorphosed to hematite. On the other hand, randomly oriented bundles of chlorite were produced from the mica of the groundmass.

The mineral facies corresponding to the different parageneses represented in these rocks are indicated in table 1 following the WINKLER's (1967) nomenclature.

## CONCLUSIONS

1. The rocks of the Caldera Unit (Sierra Nevada) are polymetamorphic: A dynamothermical regional metamorphism of Alpine age has been superimposed on a pre-Alpine thermal one.

2. Among the more noteworthy mineralogical transformations which have taken place during this evolution, two pseudomorphic processes must be emphasized: Chiastolite by kyanite, and biotite by garnet.

3. The Alpine metamorphism appears to be clearly plurifacial. Several mineralogenetic as well as deformation-stages have been distinguished as shown in table 1.

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