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# APPLICATION OF SCHREINEMAKERS' METHOD TO A METAMORPHIC AREA LOCATED AT THE NORTHERN FLANK OF THE MENDERES MASSIF (WESTERN TURKEY)

O.CANDAN*, O.DORA*

ABSTRACT

In the study area, the rock succession of the Menderes Massif includes gneisses at the base and schists at the upper levels. The trend of progressive metamorphism, from garnet-mica schists at the top of the sequence to the sillimanite-garnet gneisses at the bottom was drawn on a simplified P/T diagram after the Schreinemakers' method. The metamorphic trend beginning by "almandine+chlorite+muscovite" paragenesis passes through the fields where "staurolite+almandine+quartz (biotite)", "almandine+staurolite+kynanite+sillimanite(+biotite)" and "almandine+kyanite+sillimanite+quartz(+biotite)" associations are stable. Around the invariant point of (QUARTZ) the trend curves downward and enters the field where "orthoclase+sillimanite-almandine+muscovite(+biotite)" paragenesis is stable, the onset of high-grade metamorphism. The downward bending of this trend is also reflected by the transformation of kyanite to andalusite in pegmatoids and schists.

## I. INTRODUCTION

The Menderes Massif, which is exposed in Western Anatolia, Turkey, is located between the Izmir-Ankara Zone in the north and west and the Lycian nappe pile (Taurid Belt) in the south. There have been many different interpretations regarding the origin of the rock units and the age of the metamorphic events that have affected the Menders Massif.



*Department of Geological Engineering, University of Dokuz Eylül, 35100, Bornova/İzmir-Turkey.

There are three main hypothese concerning the age of the protoliths and the timing of the last metamorphism of the Menderes Massif. According to Önay (1949) and Schuiling (1962), the age of the last metamorphism is Variscan. In contrast to this, the Jurassic age has been suggested by Brinkmann (1966, 1967). Recent studies (Gutnic et al., 1979; Çağlayan et al., 1980; Şengör et al., 1984; Konak et al., 1987; Dora et al., 1987, 1990) have shown that the sedimentation of the protoliths of the schist and marbles continued up to the Early Eocene and metamorphism of the core and the envelope took place during the Late Eocene, in relation to the thrusting of the Lycian nappes. This metamorphism occured under MP/HT conditions.

It is known since a long time that the northern part of the Menderes Massif, the Demirci-Gördes Submassif, is rich in index minerals such as garnet, staurolite, kyanite and sillimanite. In order to determine the metamorphic evolution in this part of the Massif, the Schreinemakers method was applied on a characteristic area between the towns of Demirci and Borlu (Fig 1). We have to stress upon the fact that the present application of Schreinemakers method is of a preliminary nature. Further elaboration on the results is in preparation.

## II. LITHOSTRATIGRAPHY

The metamorphic rocks of the Menderes Massif occur as the basement of the study area. The contacts between the allochthonous units,consisting of dominantly flysch, serpentinite and limestone, and the metamorphic basement are tectonic. Both the allochthonous and metamorphic units are unconformably overlain by the Neogene aged sedimentary and volcanic rocks (Fig.2).

The fine-grained sillimanite-garnet gneisses occur in the lowest level of the study area. Widespread pegmatitic leucosomes produced during high-grade metamorphism are observed near the upper contacts of these rocks. The gneisses are conformably overlain by the kyanite-bearing schists, sillimanite-garnet-kyanite schists at lower levels and sillimanite-staurolite-garnet-kyanite schists at the upper levels. Widespread kyanite-andalusite pegmatoid occurrences are also observed in these kyanite schists which contain sillimanite-garnet mica schist and muscovite-quartz schist interlayers with highly variable thicknesses.

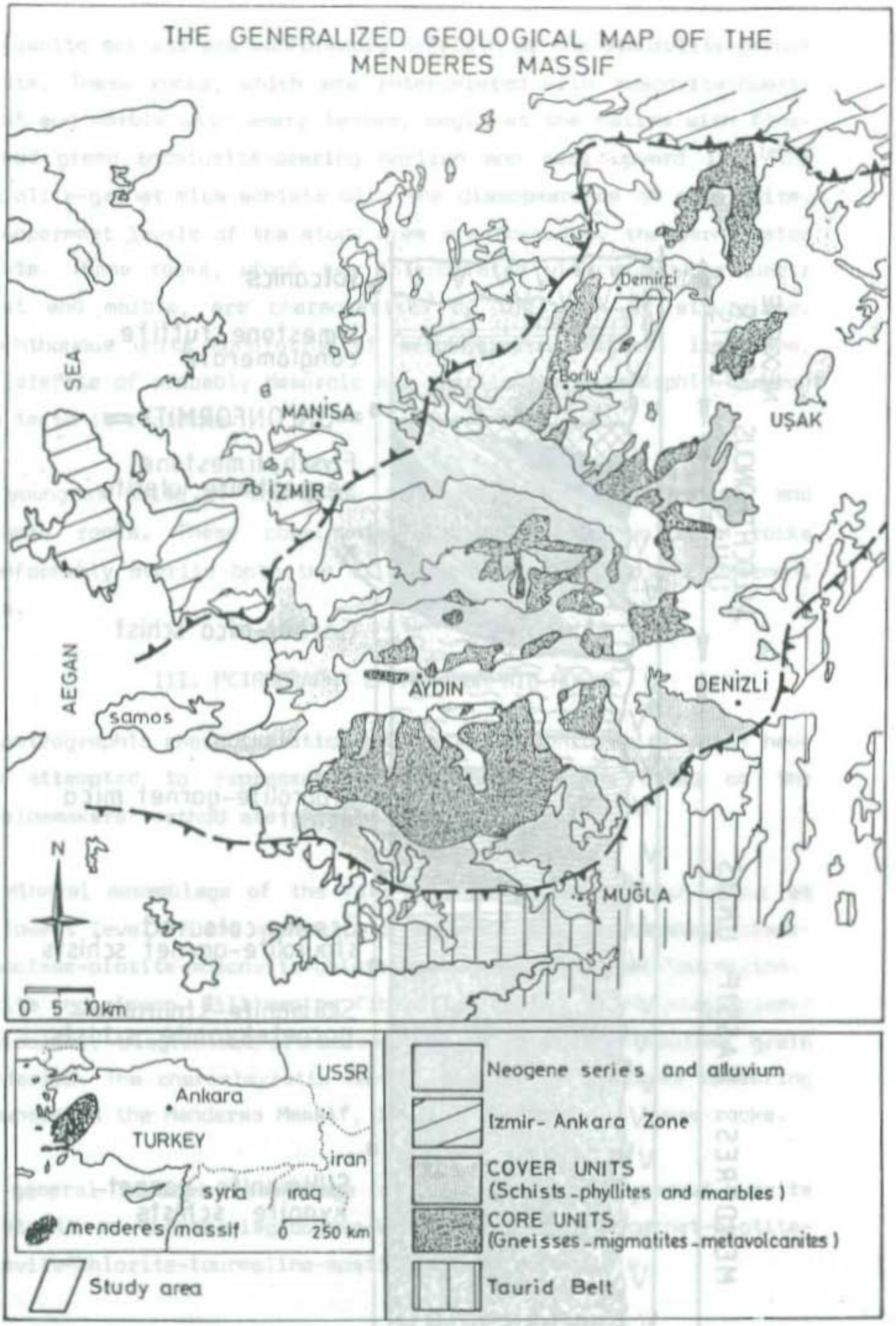



Figure 1: Sketch map of the Menderes Massif and location of the study area (taken from Dora et.al. 1990).

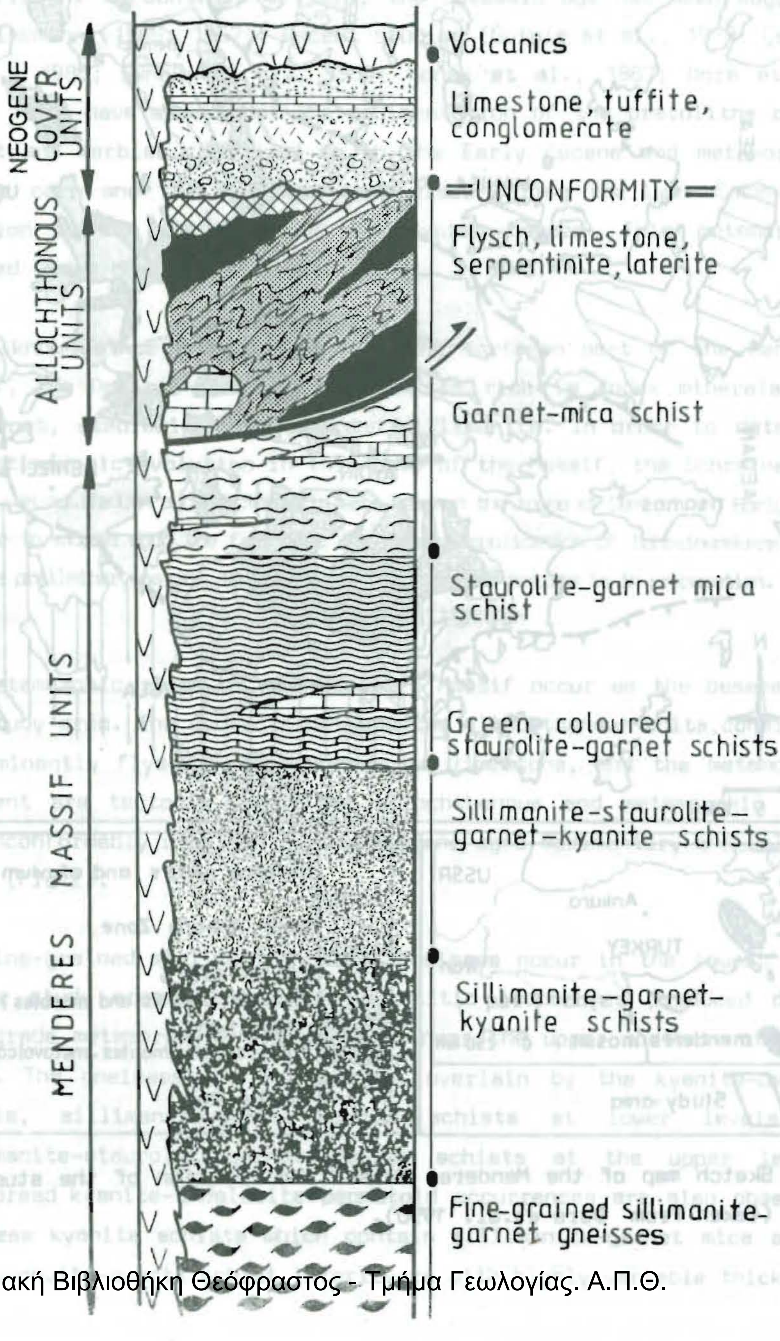





Figure 2: Generalized columnar section of the region.

The kyanite schists are conformably overlain by the staurolite-garnet schists. These rocks, which are intercalated with muscovite-quartz schist and marble with emery lenses, begin at the battom with fine-grained green andalusite-bearing horizon and pass upward into the staurolite-garnet mica schists with the disappearance of andalusite. The uppermost levels of the study area are formed by the garnet-mica schists. These rocks, which are intercalated with muscovite-quartz schist and marble, are characterized by the lack of staurolite. Allochthonous units consisting of serpentinite, flysch, limestone, and laterite of probably Mesozoic age overlie the metamorphic basement with tectonic contacts.

The youngest units of the study area are Neogene sedimentary and volcanic rocks. These continental sediments and volcanic rocks unconformably overlie both the allochthonous units and the basement units.

## III. PETROGRAPHY OF METAMORPHIC ROCKS

The petrographic characteristics of the metamorphic units which have been attempted to represent on the P-T diagram based on the Schreinemakers' method are shortly presented below.

The mineral assamblage of the fine-grained gneisses which occur at the lowest level of the metamorphic sequence are quartz-plagioclase-orthoclase-biotite-muscovite-chlorite-sillimanite-garnet-tourmaline-apatite and zircon. Sillimanite fibrolites occur at the plagioclase/plagioclase, plagioclase/orthoclase and orthoclase/orthoclase grain boundaries. The characteristic mortar texture of gneisses appearing elsewhere in the Menderes Massif, is also exhibited in these rocks.

The general mineral assemblage of the sillimanite-garnet-kyanite schists is as quartz-plagioclase-kyanite-sillimanite-garnet-biotite-muscovite-chlorite-tourmaline-apatite-zircon and rutile.

Kyanite-crystals tend to replace by sericite along fractures. Two types of sillimanite occur in these rocks. The dominant type is fibrolitic sillimanite which developed at the plagioclase/plagioclase grain boundaries. The sillimanite which was formed by transformation kyanite is the second group.

Sillimanite-staurolite-garnet-kyanite schists consist of quartz-plagioclase-biotite-muscovite-chlorite-sillimanite-andalusite-kyanite-staurolte-garnet-tourmaline-zircon-apatite and rutile. Although all of the $Al_2 SiO_5$ polymorphs are present in this unit, the most abundant is kyanite. Andalusite crystallizes in these rocks two different ways. Most of the andalusite formed by the polymorphic transformation of kyanite, the other type of andalusite is derived from muscovite. The sillimanite generally occurs as fibrolite at plagioclase/plagioclase grain boundaries and as larger crystals related polymorphic transformation of kyanite similar to those occuring in the other kyanite-bearing schists. The staurolite porphyroblasts typically breakdown to chlorite along fractures. The sillimanite-staurolite-garnet-kyanite schists have lepidoblastic and porphyroblastic textures.

Staurolite-garnet comprises two different rock groups. The green coloured, andalusite-bearing staurolite-garnet schists, up to 15 m thick, occur at the lowest level of this unit and passes upward into staurolite-garnet mica schists that contain marble and muscovite-quartz schist interlayers. The mineral assemblage of the green staurolite-garnet schists are as quartz-plagioclase-biotite-muscovite-staurolite-garnet-andalusite-chlorite-apatite and zircon. The andalusite typically occurs in the fine-grained groundmass and is derived from muscovite. The staurolite-garnet mica schists are rich-in biotite and muscovite and contain small anhedral staurolite and almandine-rich garnet crystalls. The staurolite-garnet mica schists are composed of quartz-plagioclase-biotite-muscovite-chlorite-staurolite-garnet-apatite-zircon-tourmaline. Garnet-mica schists occupy the highest level of the metamorphic succession and include mica schist garnet-mica schist, muscovite-quartz schist and marble intercalations. The mineral assemblage of the garnet-mica schist are quartz-plagioclase-biotite-muscovite-chlorite-garnet-apatite-zircon-tourmaline. Garnet anhedral crystals, the only index mineral in this unit, were widely altered to chlorite.

## IV. APPLICATION OF SCHREINEMAKERS' METHOD TO THE METAMORPHIC ROCKS OF THE STUDY AREA

The evolution of metamorphism, the appearance and disappearance of key minerals and the stability fields of the mineral assemblages in regional metamorphic terrains have been generally represented on P/T diagrams. Two main methods have been used for these representations. One is mathematical, most notably known through the work of Morey and Williamson (1918) and Morey (1936). The second main line of representation is geometric, based upon graphical analysis. The classics in this latter method are a series of 29 articles by Schreinemakers (1915-1925). This graphical approach to phase, diagrams has been adopted by most classic texts, e.g. Niggli (1930, 1954), Korzhinskii (1959) and Zen (1966).

This geometric method was applied to rocks of the study area. The total phases of the metamorphic units are quartz-plagioclase-orthoclase-chlorite-staurolite-almandine-sillimanite-andalusite-kyanite-apatite-biotite-muscovite-zircon-tourmaline and titanite (Fig.3) and, they consist of "$SiO_2$-$Al_2O_3$-$CaO$-$K_2O$-$Na_2O$-$Fe_2O$-$Fe_2O_3$-$MnO$-$MgO$-$TiO_2$-$P_2O_5$-$B_2O_3$-$ZrO_2$ and $H_2O$" (Fig.3).

Because of the impossibility of constructing such a complex system, some simplifications on the phase and component numbers were made and all the possible systems were examined by a computer program (Candan et.al. 1990). Tourmaline, zircon, rutil, apatite and sphene occur in less than 1 weight percent of the rocks. So, these accessory minerals and some components such as $ZrO_2$, $P_2O_5$, $TiO_2$ and $B_2O_3$ can be omitted in the system. Plagioclase and biotite are present in all the units. These minerals were assumed as additional phases which were stable throughout the system and therefore some components such as, $CaO$ and $Na_2O$ were eliminated. Kyanite, andalusite, and sillimanite are the polymorphs of $Al_2SiO_5$ and were regarded as a single phase in the system.

It is suggested that the most appropriate system for this area consists of the phases of "quartz-muscovite-chlorite-staurolite-almandine-$Al_2SiO_5$-orthoclase" and the components of "$SiO_2$-$Al_2O_5$-$FeO$-$K_2O$". The quaternary system with seven phases and the chemographic relations were drawn in perspective, in gram formula proportions of the oxides, are shown in

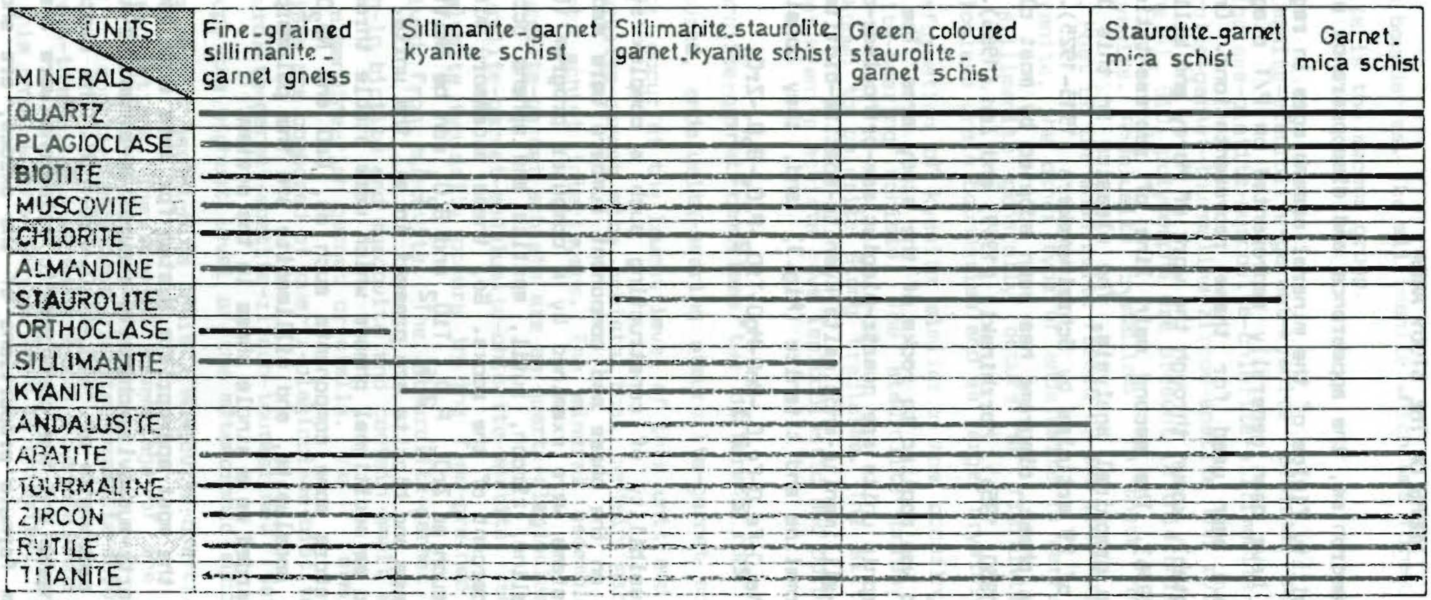



Figure 3: Mineral composition of the metamorphic rock units and appearance disappearance of the index minerals.

| | | | $SiO_2$ | $Al_2O_3$ | FeO | $K_2O$ | $H_2O$ |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | (Qz) | QUARTZ | 1 | 0 | 0 | 0 | 0 |
| $Fe_5Al_2Si_3O_{18}H_8$ | (Chl) | CHLORITE | 3 | 1 | 5 | 0 | 4 |
| $KAl_3Si_3O_{12}H_2$ | (Ms) | MUSCOVITE | 3 | 3/2 | 0 | 1/2 | 1 |
| $FeAl_4Si_2O_{12}H_2$ | (St) | STAUROLITE | 2 | 2 | 1 | 0 | 1 |
| $Fe_3Al_2Si_3O_{12}$ | (Alm) | ALMANDINE | 3 | 1 | 3 | 0 | 0 |
| $Al_2SiO_5$ | (Al-Silicate) | AL.SILICATE | 1 | 1 | 0 | 0 | 0 |
| $KAlSi_3O_8$ | (Ort) | ORTHOCLASE | 3 | 1/2 | 0 | 1/2 | 0 |

+ BIOTITE
+ PLAGIOCLASE

The phases which are stable throughout the system

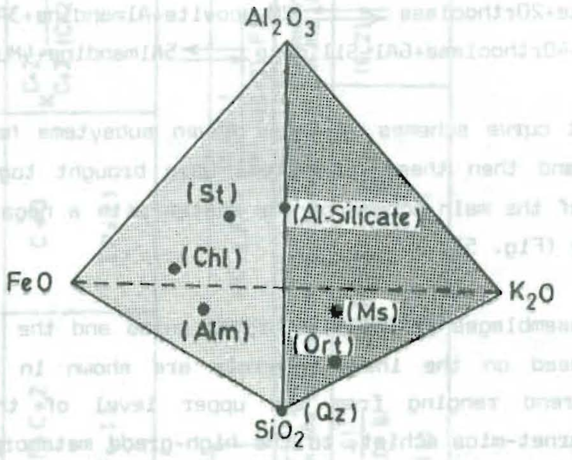



Figure 4: The quaternary system with seven phases and the chemographic relations drawn in perspective, in gram formula proportions of the oxides.

The elements of the main system (i.e., total number of the univariant points, total number of the univariant curves, e.t.c) with the value of freedom F= -1 calculated by the Gibbs-phase rule and combinatorial formula, are given in Table 1. These main system (F=-1) was divided into seven subsystems. The elements of these subsystems were calculated by the same formula (Table 1) and all possible reactions between the phases for each subsystems were written. Because of the compositional coincidences between the phases in the system, some degenerations were occurred. Therefore, only 13 distinct univariant reactions can be written for the main system. These reactions are as follows :

1) Chlorite+4Al-Silicate $\rightleftarrows$ Almandine+2Staurolite+2$H_2O$
2) 3Staurolite+2Quartz $\rightleftarrows$ Almandine+5Al-Silicate+3$H_2O$
3) 4Quartz+3Chlorite+2Al-Silicate $\rightleftarrows$ 5Almandine+12 $H_2O$
4) Chlorite+9Al-Silicate+$H_2O$ $\rightleftarrows$ 2Quartz+5Staurolite
5) 5Chlorite+2Staurolite+8Quartz $\rightleftarrows$ 9Almandine+2$H_2O$
6) Chlorite+9Muscovite+7Quartz $\rightleftarrows$ 9Orthoclase+5Staurolite+8$H_2O$
7) Chlorite+2Muscovite+7Al-Silicate $\rightleftarrows$ 2Orthoclase+5Staurolite+$H_2O$
8) Muscovite+Quartz $\rightleftarrows$ Orthoclase+Al-Silicate+$H_2O$
9) 3Chlorite+6Staurolite+8Orthoclase $\rightleftarrows$ 7Almandine+8Muscovite+10$H_2O$
10) 3Staurolite+5Orthoclase+2$H_2O$ $\rightleftarrows$ 3Muscovite+Almandine+3Quartz
11) 3Chlorite+2Muscovite+6Quartz $\rightleftarrows$ 5Almandine+2Orthoclase+14$H_2O$
12) 3Staurolite+2Orthoclase $\rightleftarrows$ 2Muscovite+Almandine+3Al-Silicate+$H_2O$
13) 3Chlorite+4Orthoclase+6Al-Silicate $\rightleftarrows$ 5Almandine+4Muscovite-8$H_2O$

The univariant curve schemes of these seven subsytems have been drawn individually and then these subsystems were brought together for the construction of the main scheme of the system with a negative degree of freedom (F=-1) (Fig. 5).

The mineral assemblages of the metamorphic units and the isograd map of the region based on the index minerals are shown in Figure 6. The metamorphic trend ranging from the upper level of the metamorphic succession, garnet-mica schist, to the high-grade metamorphic series at the bottom, sillimanite-garnet gneiss, was drawn on this map.

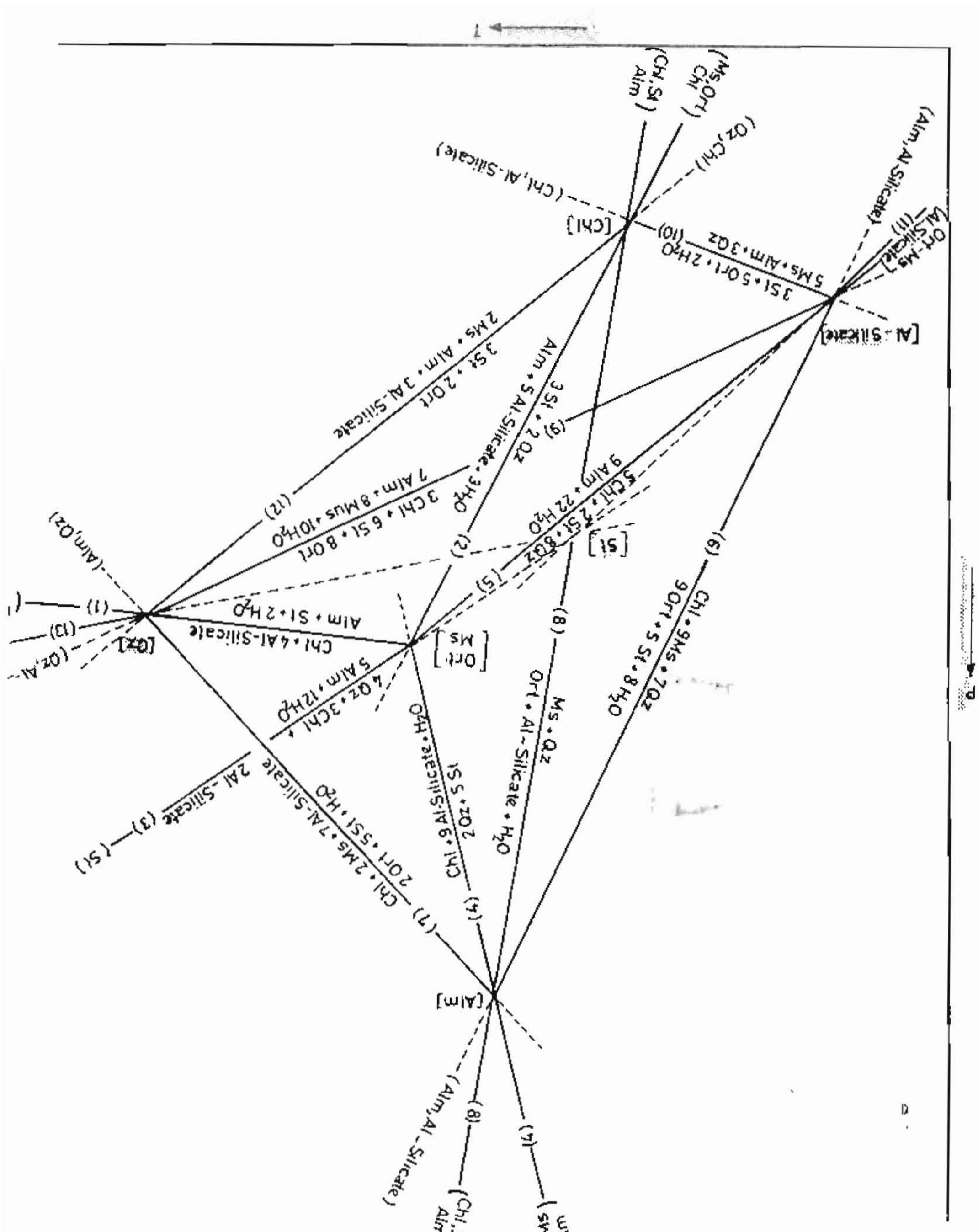
C = 4

| (Number of degrees of freedom) | (Total number of phases) | (Total number of invariant points in the system) | (Total number of the univariant curves) | (Number of the invariant points on the univariant curves) |
|---|---|---|---|---|
| $P+F=C+2$ | $C+3$ | $K_{C+3}^{C+2}=\frac{(C+2)!}{(C+2)!\,[(C+3)-(C+2)]!}$ | $K_{C+3}^{C+1}=\frac{(C+3)!}{(C+1)!\,[(C+3)-(C+1)]!}$ | $F+1$ |
| (F = 1) | (P = 7). | (7) | (21) | (2) |

C = 4; $(C+2,F)=\frac{(C+2)!}{F!\,[(C+2)-F]!}$; $P+F=C+2$

| (Number of invariant points in the system) | (Number of univariant curves and reactions) | (Number of the assemblages in the fields) | (Number of phases on the invariant point) | (Number of phases on the curves) | (Number of phases in the fields) |
|---|---|---|---|---|---|
| $(6,0)=\frac{6!}{0!\,6!}$ | $(6,1)=\frac{6!}{1!\,5!}$ | $(6,2)=\frac{6!}{2!\,4!}$ | $P+F=C+2$ | $P+F=C+2$ | $P+F=C+2$ |
| (1) | (6) | (15) | (6) | (5) | (4) |

Table 1: The calculation of the elements of the main system and the seven subsystems by the Gibbs-phase rule and combinatorial formula.


[Chl]
[Al-Silicate]
[Qz]
[Ort Ms]
[St]
[Alm]
(Chl,St Alm)
(Ms,Ort Chl)
(Qz,Chl)
(Chl, Al-Silicate)
(Alm, Al-Silicate)
(Al-Silicate)
(Ort-Ms)
(Alm,Qz)
(Qz,Al-
(Ort,Ms Alm)
(St)
5 Ms + Alm + 3 Qz
3 St + 5 Ort + 2 H2O
2 Ms + Alm + 3 Al-Silicate
3 St + 2 Ort
Alm + 5 Al-Silicate + 3 H2O
3 St + 2 Qz
7 Alm + 8 Ms + 10 H2O
3 Chl + 6 St + 8 Ort
9 Alm + 22 H2O
5 Chl + 2 St + 8 Qz
Alm + St + 2 H2O
Chl + 4 Al-Silicate
5 Alm + 12 H2O
4 Qz + 3 Chl +
2 Al-Silicate
Chl + 2 Ms + 7 Al-Silicate
2 Ort + 5 St + H2O
Chl + 9 Al-Silicate + H2O
2 Qz + 5 St
Ms + Qz
Ort + Al-Silicate + H2O
Chl + 9 Ms + 7 Qz
9 Ort + 5 St + 8 H2O
P
T

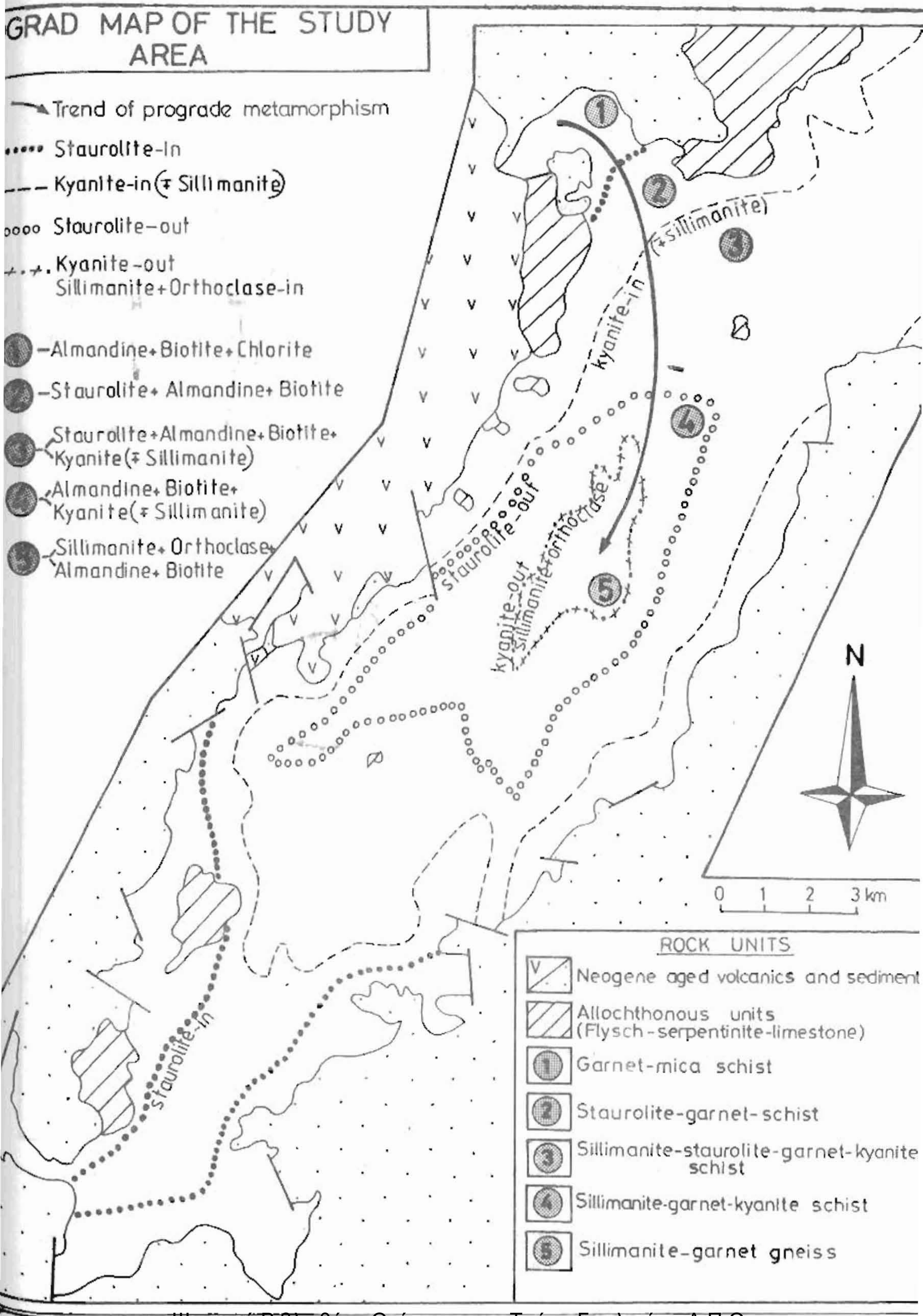





**Figure 6:** The mineral assemblages of the metamorphic units and the isograd map of the region based on the index minerals (after

In order to simplify this main scheme, some of the invariant points, which are believed to be not important in this region, were omitted and a simplified P/T diagram consisting of only the invariant points of the [ORTHOCLASE/MUSCOVITE] - [QUARTZ] - [CHLORITE] subsytems, was obtained. This diagrams was properly oriented based on the reaction which has been experimentally studied by Richardson (1968 ,Figure 7). The reaction proposed for the formation of staurolite in the pelitic schists by Froese and Gasparrini (1975) is conformed by the petrographical and textural evidences of the study area and this reaction is also added to the scheme. The metamorphic evolution of the region, from low-grade to high-grade metamorphism, is shown on this simplified diagram. The metamorphic trend which begins with "almandine-chlorite-muscovite" paragenesis in garnet-mica schists at the top of the metamorphic series passes through the fields where "staurolite+almandine+quartz(+biotite)", "almandine+staurolite+kyanite(+sillimanite)(+biotite)" and "almandine+kyanite(+sillimanite)+quartz(+biotite)" parageneses which were respectively observed in the staurolite-garnet schists, sillimanite-staurolite-garnet-kyanite schists and sillimanite-garnet-kyanite schists are stable. Around the invariant point of [QUARTZ] the trend curves downward and enters the field where "orthoclase+sillimanite+almandine+muscovite(+biotite)" paragenesis is stable, the onset of high-grade metamorphism. The downward bending of the trend was a result of decreasing pressure; it may have caused the common polymorphic transformation from kyanite to andalusite in kyanite-andalusite pegmatoids and kyanite schists. It is assumed that the decrease of pressure in the region resulted from the rapid uplift of the Menderes Massif during the Early Oligocene time and erosion of the Lycian nappes rest upon the Massif. The preserved remnants of the Lycian nappes at the study area supports this assumption.

## CONCLUSIONS

It was concluded from the successive facies series observed in this region, that the study are located at the Demirci-Gördes Submassif of the Menderes Massif was subjected to the Barrovian-type MP/HT metamorphi The appearance and disappearance of the index minerals and the stability fields of the mineral assamblages determined for this region attempted

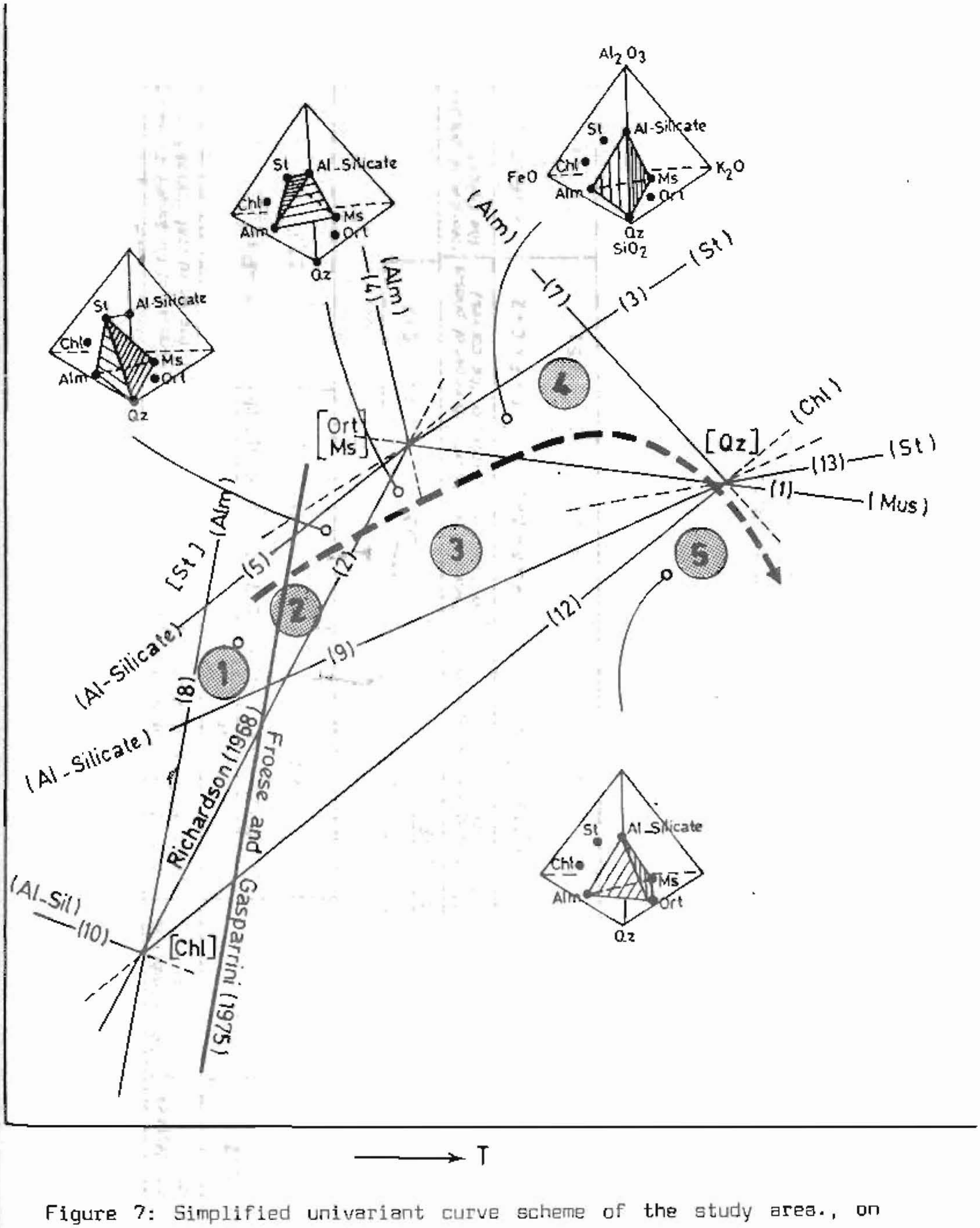



Figure 7: Simplified univariant curve scheme of the study area., on the P-T path.

to plot on the Schreinemakers' P/T diagram of multicomponet system with a negative degree of freedom (F=-1). The metamorphic trend which passes from the low-grade into high-grade metamorphic series was drawn on the diagram oriented according to the experimentally studied reactions. The downward bending of the trend, which was caused from the decrease of pressure during the last stage of the metamorphism is consistent with the observations of the widespread polymorphic transformations of kyanite to andalusite. It is considered that the decrease in pressure in the region resulted from the rapid uplift of the Menderes Massif and accompanying removal of the overlying pile of the Lycian nappes through erosion.

This study further supports that the Schreinemakers' method can be successfully applied to clarify the metamorphic terrains with successive subfacies series and index minerals.

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