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POLYMETAMORPHIC EVOLUTION OF THE PAN-AFRICAN BASEMENT AND PALAEOZOIC-EARLY TERTIARY COVER SERIES OF THE MENDERES MASSIF

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ABSTRACT.- The Menderes Massif exposing in the Western Anatolia substantially presents a complex tectonostratigraphy as a result of Late Alpine compressional tectonism. The lithostratigraphical succession of this crystalline complex can be divided into two units: 1- The Pan-African basement (core series) and 2-Palaeozoic - Early Tertiary metasedimentary rocks (cover series). The Pan-African basement of the Menderes Massif is made up of a Late Neoproterozoic metaclastic sequence consisting of paragneisses and conformably overlying micaschists. This high-grade metaclastic sequence is extensively migmatized and intruded by the syn- to post-Pan-African gabbros and granitoids. The primary contact relationship between the core and cover series is a regional unconformity in character. The Palaeozoic (?Upper Devonian - Permian) cover units, which are cut by the intrusion of Triassic leucocratic metagranites are consisted of phyllites, quartzites and marbles. The Mesozoic cover units are characterized by Triassic to Upper Cretaceous platform-type thick marbles at lower levels of the sequence. Upper Campanian - Upper Maastrichtian pelagic carbonates and the overlying Middle Paleocene - Eocene flysch-type blocky unit constitute the uppermost units of cover series. Relic mineral assemblages observed in the Pan-African basement reveal a complex polyphase metamorphic evolution of this basement under granulite, eclogite and amphibolite-facies conditions. The high temperature metamorphism developing under granulite facies is characterized by the presence of hypersthene type pyroxene. Pelitic granulites, orthopyroxene gneisses, orthopyroxene paragneisses and metagabbroic / metanoritic rocks form typical granulite-facies relics observed in the massif. Geothermobarometric estimations characterize an average temperature of 730 °C and pressure of 6 kbar for the granulite-facies metamorphism. By means of SHRIMP II method, clustering ages of 583±5.7 Ma were dated from the outer parts zircons in pelitic granulites which have no zoning but have overgrown under granulite facies. High grade metamorphism relics in the Pan-African basement are characterized by eclogite and eclogitic metagabbros. Fully recrystallized, fine grained massif eclogites, with non bearing relic texture belonging to protolith are composed of 'omphacite (jd_{40-52}) + garnet + clinozoisite + amphibole + quartz + rutile'. However; relic texture and minerals are extensively observed in metagabbros derived from eclogitic gabbros. The pressure-temperature (P-T) conditions of the Pan-African high-pressure metamorphism were estimated as 644°C with a minimum pressure of about 15 kbar, which corresponds to a burial depth of about 50 km. ^{206}Pb/ ^{238}U zircon ages obtained from eclogitic metagabbros by TIMS yield 529.9±22 Ma, reveal the high-pressure metamorphism as Pan-African in age. The Barrowian type medium pressure metamorphism reaching up migmatization stage in which anatectic granites developed caused extensive retrogradations. Geothermobarometric estimates from garnet amphibolites, retrograded from eclogites indicate that this metamorphism developed under P/T conditions of 7 kbar in pressure and 628°C in temperature. The crystallization ages of these anatectic granites range from 551 to 540 Ma. They were generated by migmatization of paragneisses and reveal that this medium-pressure event is related to the last stage of polyphase Pan-African metamorphism. All metamorphic ages obtained from the Pan-African basement are compatible with the latest stages of assemblage of Gondwana super continent. It is considered that protoliths of paragneisses and schists of the Pan-African basement were deposited on a passive continental margin of a basin occurring between East and West Gondwana during the Late Proterozoic time (Mozambique Ocean). The Pan-African basement of the Menderes Massif was deeply buried and metamorphosed under granulite, eclogite and amphibolite-facies conditions as a result of the closure of this basin and collision of East and West Gondwana during Late Neoproterozoic time. Both core and cover series of the Menderes Massif were affected by an Alpine aged old regional metamorphism. In the Palaeozoic sequence of

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cover series, this metamorphism is characterized by a Barrowian type medium-pressure metamorphism. This metamorphism developed under greenschist to lower amphibolite-facies (6 kbar in pressure / 430-550 °C in temperature) and described by the occurrences of garnet, staurolite and kyanite (disthene) in phyllites. Mesozoic-Early Tertiary cover series at the southern part of Çine submassif contain data associated with Alpine aged HP/LT metamorphism. Carpholite-kyanite assemblage within Triassic quartz metaconglomerates shows a metamorphism under a pressure of 10-12 kbar and temperature of 440 °C corresponding to a minimum depth of 30 km. So far, there has not been detected any data for an Alpine HP / LT metamorphism, neither in the Pan-African basement nor in the Palaeozoic sequence of the Menderes Massif. Based on the fossil content obtained from youngest unit of the cover series and from the oldest non metamorphic sedimentary cover on the massif, the Alpine metamorphism can biostratigraphically be constrained into Eocene and Oligocene time interval. Few isotopic data (37±1 Ma, Late Eocene Rb/Sr biotite age; 36±2 Ma, Middle Eocene Ar/Ar muscovite age; 43-37 Ma, Eocene Ar/Ar muscovite age) related to Alpine metamorphism are compatible with the related time interval. The Alpine metamorphisms of tectonical zones belonging to Anatolides is substantially associated with the closure of the northern branch of Neothethys Ocean and with the collision in Paleogene. In such a tectonic model, the segment of the Anatolide-Tauride platform corresponding to the Menderes Massif was subjected to intense internal imbrication during the subduction process of the northern branch of Neotethys and the following period in which the continental collision occurred. The tectonical slices being formed were buried at different depths and metamorphosed under varying conditions related with burial depths under the load of Afyon zone at north in Eocene-Oligocene times, and of Lycian nappes passing south and of ophiolites.

Key words: Menderes Massif, Pan-African Orogeny, metamorphism, granulite, eclogite, carpholite.

INTRODUCTION

NE-SW trending the Menderes Massif crops out in Western Anatolia pervasive and is one of the best studied crystalline regions of Turkey. This crystalline complex is tectonically overlain by Lycian nappes at south, by Izmir-Ankara suture zone at north and northwest and by the extension of Cycladic complex in Turkey. This massif is constrained by low grade metamorphics belonging to Afyon zone at the north and covered by the Neogene sedimentary /volcanic units at the east. E-W trending young graben systems divide the Menderes Massif into three sub massifs as; Demirci Gördes submassif (northern submassif), Ödemiş-Kiraz submassif (central submassif) and Çine submassif (southern submassif) (Figure 1).

For many years, it has been considered by many investigators that the Menderes Massif is made up of a simple and uniform stratigraphy by Precambrian core and by the surrounding Palaeozoic-Early Tertiary cover series all around (Schuiling, 1962). However, recent studies have clearly revealed that thrust faults produced by the Late Alpine compressional tectonic have largely reshaped the primary stratigraphy of the Massif (Konak et al., 1994; Partzsch et al., 1998; Ring et al., 1999; Gökten et al., 2001). The primary contact relationship between the core and cover series can today be observed in very rare areas (Pan-African unconformity; Şengör et al., 1984; Konak et al., 1987; Dora et al., 2005; Candan et al., 2006). This contact relationship between these units is defined by thrust faults in many places. The stratigraphy of core and cover series at present have largely been brought to light by the determination of tectonostratigraphies of these tectonic units and by its correlation with each other (Konak et al., 1987; Dora et al., 2001, 2005). The general distribution of core and cover series in massif scale so called as the "Pan-African basement" and also as the "Precambrian basement" is shown in figure 1.

The overall metamorphic structure of the Menderes Massif was acquired by the Alpine age latest metamorphism which is also named as the Main Menderes Metamorphism and this opinion has generally been accepted by many investigators (Şengör et al., 1984). However, in recent years many new evidences has been obtained showing that the Menderes Massif has a more

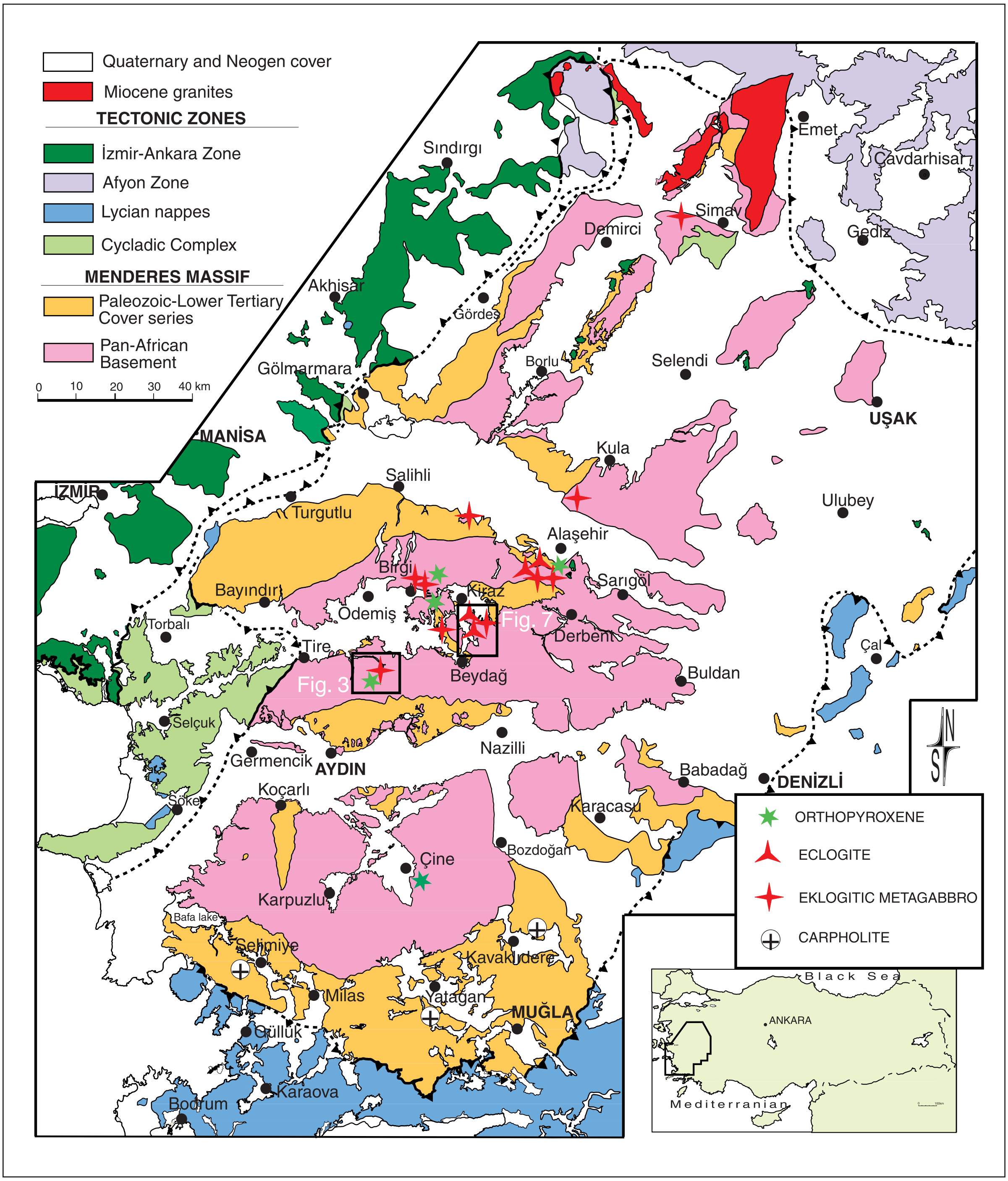

Figure 1- The distribution of the Pan-African Basement and Palaeozoic-Early Tertiary cover series throughout the Menderes Massif. Locations where relics of Pan-African aged granulite-eclogites facies metamorphism and Alpine age high pressure metamorphism are shown on map.

complex metamorphic history than had ever been considered. Petrological evidences indicate that the Precambrian basement in the Menderes Massif was affected by the polyphase metamorphism associated with the Pan-African orogeny under granulite, eclogite and amphibolite facies (Candan and Dora, 1998; Candan et al., 1994, 1995, 2001, 2007; Oberhänsli et al., 1995*a-b*, 1997). However in cover series, new evidences have been obtained defining HP / LT metamorphism conditions in addition to widespread Barrowian type medium pressure metamorphism assemblages in cover series (Rimmelé et al., 2002, 2003). In this article, the Pan-African basement and poly metamorphic evolutions of Palaeozoic-Early Tertiary cover series of the Menderes Massif has been reevaluated. The article prepared within this context mainly aims at presenting and discussing the data on; 1- petrographical / petrological properties, ages of polyphase metamorphism observed in the Pan-African basement of the Menderes Massif, and its relationships with the Pan-African orogeny and 2- the poly metamorphism of cover series and temporal and spatial relationships of these series with the evolution of Neothethys Ocean.

THE LITHOSTRATIGRAPHY OF THE MENDERES MASSIF

Recent studies have largely established that the massif has lost its original stratigraphy by the Alpine age compressional tectonism (Konak et al., 1994; Partzsch et al., 1998; Ring et al., 1999; Gökten et al., 2001). At present, units that belong to the Pan-African basement are observed as tectonical slices presenting imbrications with Palaeozoic-Early Tertiary cover series. The generalized columnar section of the Menderes Massif obtained by the tectonostratigraphy of tectonic slices and its correlation with each other is given in figure 2. As seen in the figure, the stratigraphy of the Menderes Massif is divided into two main units as; 1- Late Neoproterozoic Pan-African basement and 2- Palaeozoic-Early Tertiary cover series. The primary contact between these two units is in character of regional unconformity defining a deep erosion (Pan-African unconformity; Şengör et al., 1984; Konak et al., 1987; Candan et al., 2006).

The oldest rock units of the Pan-African basement are composed of metaclastics forming a regular and continuous sequence. Related metaclastic sequences are cut by granitoid and gabbroic rocks that have intruded at various stages of Pan-African orogeny. This metaclastic sequence has a minimum thickness of 8 km and is divided into two units as; i) paragneiss and ii) schist (from bottom to top) (Dora et al., 2001). The paragneiss unit forming the lower unit of metaclastic sequence is composed of two lithologies showing both lateral and vertical transitions. The dominant lithology is paragneiss derived from litarenitic sandstones and containing sillimanite (± orthopyroxene). The schists rich in garnet and sillimanite which show lateral and vertical transitions with paragneisses form the other lithology. Although there are many transitional type lithologies, the mica schist and biotite albite schists derived from the mudstone and sub arkosic sandstones form dominant schist types. The true thickness of the paragneiss is not known as its lower levels are cut by thrust faults and / or it includes granitic inclusions. However, 4 km the apparent thickness of a slice observed in Kula region is accepted as the maximum thickness of paragneiss unit in the Massif. Paragneiss unit is conformably and transitionally overlain by the schist unit. Schist unit is dominantly composed of mica schist and biotite albite schist intercalations of which its protoliths correspond to mudstone and sub arkose. Probably at the upper levels of these schists, black quartzite layers that have a thickness not exceeding 0.5 m are rarely observed. On the other hand, these schists are conformably and transitionally overlain by a deposit made up of muscovite schist / biotite, muscovite, quartz schist intercalation located at the southern part of Çine submassif. These schists show an approximate thickness of 2 km and present probably the uppermost levels of the schist unit belonging to the Pan-African basement. Within schist unit,

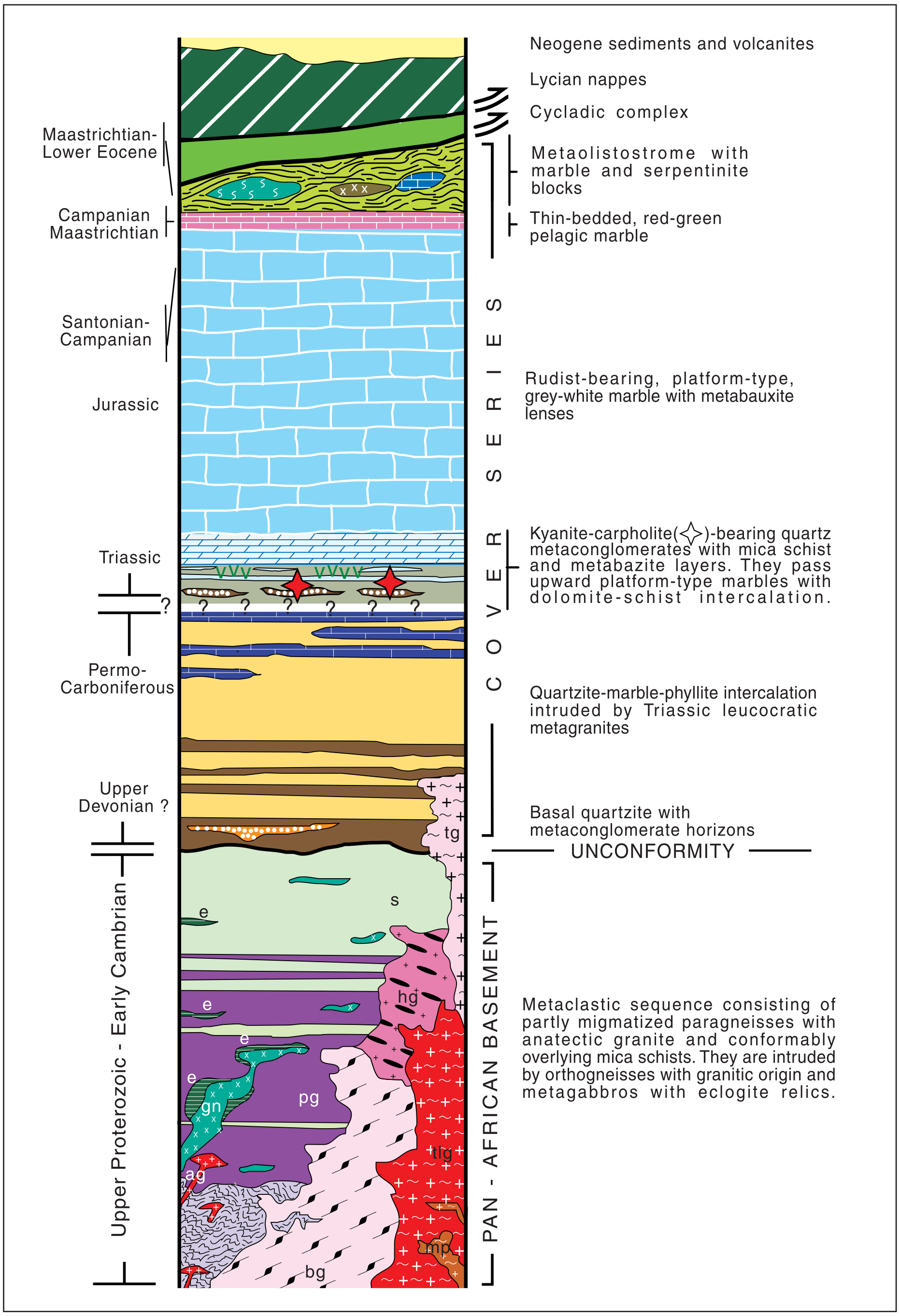

Figure 2- Generalized columnar section of the Menderes Massif (gn:Gabbro-norite, ag:Anatectic granite, tg:Triassic leucocratic orthogneiss, hg:Hornblende orthogneiss, bg:Biotite orthogneiss, tlg:Tourmaline leucocratic orthogneiss, pg:Paragneiss, s:Schist, e:Eclogite, modified from Dora et al., 2001).

dolomitic marble lenses can very rarely be observed with a dimension of 80x200 m. Paragneiss unit forms the lowermost layers of the metaclastic sequence and show a widespread migmatization throughout the Massif. These migmatites are accompanied by anatectic granites which were produced by partial melting in many places.

Both schist and paragneiss units are cut by numerous basic magmatic rocks with a character of stock and vein reaching up to a 1.5 km in dimension. These Precambrian / Cambrian rocks are composed of biotite gabbro, olivine gabbro, noritic gabbro, norite and display extensive transformations into eclogite and amphibolites along their peripheral zones (Candan et al., 2001). The orthogneisses made up of plutons that have intruded into each other are granitic in origin and form one of the most widespread rock type belonging to the Pan-African basement. Orthogneisses in the massif can be divided into many sub-types like, biotite orthogneiss, tourmaline leucocratic orthogneiss, amphibole orthogneisses, metagranite porphyry, albite and metaaplitic vein rocks rich in quartz in granoblastic textures by basing on the texture and mineralogical composition of the primary granites (Bozkurt, 2004; Dora et al., 2005). These orthogneiss types defining a Precambrian / Cambrian aged (varying between 570-520 Ma; average 550 Ma; Loos and Reischmann, 1999) acidic magmatic activity, present clear intrusive contact relationship with metaclastic sequence as the oldest rock of the Pan-African basement.

The Pan-African basement is overlain by Palaeozoic units with an unconformable contact. Palaeozoic sequence in Late Devonian(?) - Permo Carboniferous age (Çağlayan et al., 1980; Konak et al., 1987) begin with muscovite-quartz schists derived from pure quartz arenite defining an unconformity at lowermost layers. These rocks reach a thickness of 1.5 km and metaconglomerates in the form of channel fillings are observed close to the basement. These conglomerates can laterally be traced 35 km in the form of discontinuous exposures. The components of these conglomerates are composed of granite, aplite and of tourmaline pebbles in various mineralogical compositions which were derived from the Pan-African basement of the Massif. The quartzite is conformably and transitionally overlain by black colored phyllites. In these rocks bearing garnet, chloritoid, staurolite and disthene, there are gray to black colored marble layers. Fossil finding indicate that this black sequence is Permo-Carboniferous in age (Konak et al., 1987). Palaeozoic cover series are cut by leucocratic metagranites rich in quartz-feldspar minerals and rarely bear biotite. These rocks are stock and sill in character reaching a dimension of 5-6 km. Their crystallization ages were determined as 241-236 Ma (Early to Middle Triassic) by Pb/Pb method (Koralay et al., 2001). The Mesozoic units of cover series begin with a mica schist layer having a thickness of 200 m and bears meta conglomeratic channel fills and basic additives. The primary contact relationship of this assemblage of probably Upper Triassic with the Palaeozoic cover series is interpreted as a regional unconformity (Konak et al., 1987; Erdoğan and Güngör, 2004). Meta-conglomerates completely made up of quartz pebbles include disthene-chloritoid schist interbeddings derived from clay rich in aluminum and do not exceed a couple of meters in thickness. In quartz veins of pebbles, carpholite-disthene interval is observed as the product of Alpine age high pressure metamorphism Rimméle et al., 2003). Meta-conglomerate schist intercalation is conformably and transitionally overlain by platform type thick carbonates. The transition zone is defined by pink-yellow dolomite-quartzite-calc schist intercalations. This intercalation has a thickness of 50 m and overlain by gray colored massive dolomites. Meta bauxite layers are observed 150 meters above probable Upper Triassic-Lower Jurassic dolomitic carbonates. They are located in marbles with lense shaped and have a lateral continuity reaching tens of kilometers. Meta bauxites are repeated several times in massive marbles which reach a thickness of 1500 meter (Milas formation). There is not any clear data if these meta bauxites are different layers or tectonically repeated. Well preserved rudist fossils are widely observed 50-400 meters above the meta bauxite layer in the massive. These layers are Santonian-Campanian in age and can laterally be traced by tens of kilometers (Özer et al., 2001). Rudistic layers upwardly grade into intra formational limestones and cherty marbles. Cherty marbles are overlain by Upper Campanian-Upper Maastrichtian red pelagic marbles (Kızılağaç formation) which transitionally reach a thickness of 150 meters. Kazıklı formation is made up of a sandstone and shale derived matrix and marble blocks, forms the uppermost unit of the Menderes Massif. The contact relationship of this unit with red marbles are still in discuss and ages varying between Middle Paleocene to Lower-Middle Eocene were obtained (Konak et al., 1987; Özer et al., 2001).

THE METAMORPHISM OF THE PAN-AFRICAN BASEMENT

Recent evidences support the idea that main metamorphic effect shaping the Pan-African basement of the Menderes Massif is associated with the Pan-African orogeny and the Alpine metamorphism caused limited retrogradations on this basement. Petrological / petrographical and geochronological data indicate that poly phase metamorphism of the basement occurred successively under granulite, eclogite and upper amphibolite facies conditions.

THE METAMORPHISM OF GRANULITE FACIES

Petrography and mineral chemistry

Relic mineral clusters and rocks related to high temperature metamorphism under granulite facies affecting the Pan-African basement are very rarely observed in the Massif (Figure 1). Great majority of these evidences were obtained from Ödemiş-Kiraz submassif. Data defining the related metamorphism can be divided into four groups. These are; 1- Pelitic granulites, 2- Gneisses with orthopyroxene, 3- Orthopyroxene paragneisses, 4- Metagabbro / metatonalites (Candan, 1995).

The region where pelitic granulites are best observed is the southeast of Tire, around Küre village (Figure 3). The region is made up of two tectonical units belonging to the Pan-African basement (Çetinkaplan, 1995; Candan and Çetinkaplan, 2001). The lower slice is composed of biotite and garnet mica schist having a homogenous composition. The upper slice in the form of clippe and has a dimension of 6x4 km and contains all data related to a poly-metamorphic evolution of the Pan-African basement. Pelitic granulites crop out in a 1x1 km region within a clippe. Granulites are grayish rocks in massive structure. These medium to fine crystallized rocks in granoblastic texture contain black colored orthopyroxene crystals reaching 0.5 cm dimensions. Widespread calcsilicate rocks that show strong boudinage are observed within granulites. These calcsilicates are one the most characteristic lithologies that belong to the Pan-African basement and their presence indicate that paragneisses transformed into pelitic granulites in some places. Textural data reveal that these rocks have a complex metamorphic evolution. The mineral assemblage of granulite facies is composed of 'quartz + plagioclase + orthoclase + orthopyroxene + biotite + garnet +cordierite (?) + ilmenite + rutile'. Granoblastic polygonal texture with a grain boundary of 120° in angle and straight boundaries are observed defining the high temperature conditions in quartz and feldspars in these rocks (Figure 4a). Plagioclases in An_{29-31} composition contain antipertitic structures specialized to granulites. Garnets of granulitic stage are in anhedral and in the form of porphyroblasts with many quartz inclusions. Compositional homogenization developed in garnets because of the volumetric diffusion that occurred under high temperature conditions. Garnets of this stage are distinctively poor by spessartin and grossular end members but substantially rich in almadine and pyrop. The end member components of these garnets have

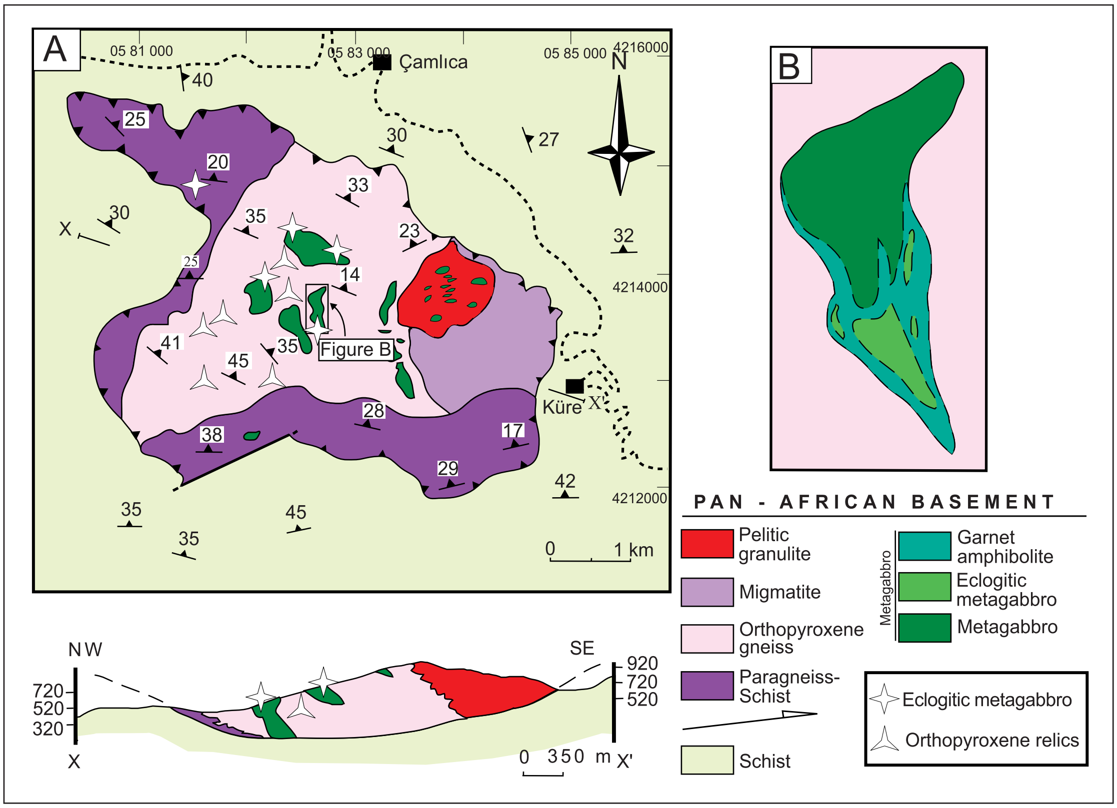

Figure 3- Geological map of Küre village and its surround, southeast of Tire. The region is made up of clippe and underlying low graded schists. Clippe is made up of high graded rocks where assemblages of granulite, eclogite and amphibolite facies belonging to the Pan-African Basement are observed. Region is shown is figure 1 (modified from Çetinkaplan, 1985).

been detected as 'Grs_{0-1} - Alm_{68-72} - Prp_{21-24} - Sps_{2-3} - And_{1-2}. The most characteristic mineral of pelitic granulites is orthopyroxene. FeO content is approximately %29 and MgO is %16 in equidimensional crystals observed granoblastic textures. These minerals are hypersthene in composition (Figure 5a) and have high Al_2O_3 amount specialized to orthopyroxenes in granulite facies. The amount of Al_2O_3 in minerals varies between 3.4%-3.8%. The metamorphic products that overlie pelitic granulites include pervasive retrogradation data. The most characteristics of these are; 1- garnet coronae developing around mafic phases, 2- replacement of orthopyroxene by biotite, 3- consumption of cordierites by high temperature ensemble, 4- replacement of biotites by sillimanite. When occurring phases are considered, it is understood that the overlying metamorphism had taken place under the conditions of upper amphibolite facies. Garnet corona developed into feldspar, along contacts of feldspars with orthopyroxene, biotite, rutile, ilmenite and garnet (Figure 4b). These garnets are rich in grossular composition and gradual increase in CaO towards plagioclase. In garnet corona the textural zoning is observed in addition to combined zoning. In general, there is a narrow intermediate zone made up of quartz between mafic phases and garnet corona. At contacts of orthopyroxene-biotite partial reaction zones developed in a way that expresses an inequality on the overlying metamorphism. Biotite porphyroblasts belonging to granulitic stage along these zones recrystallize in the form of finger type biotite - plagioclase syn - growth. However, accessory mineral which is the orthopyroxene is consumed by fine grained biotites (Figure 4c). Similar to those in paragneisses diffuse pseudomorphic replacement textures belonging to a former mineral are observed in pelitic granulites. This mineral was interpreted as cordierite based on general properties (Dora et al., 2001). These mineral holes have been filled by a high temperature ensemble made up of 'sillimanite / disthene - garnet - biotite - quartz' (Figure 4d). In addition to cordierites, biotite porphyroblasts which are the granulitic stage products are also consumed pervasively by sillimanite. The new mineral group is made up of sillimanite and of small biotites.

The great majority of orthopyroxene paragneisses were recognized in Ödemiş-Kiraz submassif (Figure 1). Except the location at south of Alaşehir, all orthopyroxene paragneisses in the massif are present as intercalations with dimensions reaching several hundreds of meters. These paragneisses are dark gray in color and fine grained massive rocks. As for the rocks at south of Alaşehir are composed of migmatites as dark brown fine grained massive rocks. Besides, the widespread presence of black speckles is known in paragneisses throughout the Massif. These speckles are made by the mineral clusters of upper amphibolite facies and are considered as the cordierites which are the metamorphism product of granulite facies that affect paragneisses (Dora et al., 2001). The general mineral assemblages of paragneisses are "quartz + plagioclase + orthoclase + orthopyroxene + biotite + ilmenite / rutile". The consumption of biotites by sillimanite, the replacement of orthopyroxenes by biotite, the development of garnet ring around orthopyroxene are the main textural evidences related to retrogradation in these rocks under amphibolite conditions (Figure 4e).

Orthopyroxene gneisses are observed in Tire and Birgi regions in the Massif (Figure 1, Figure 3). These rocks were derived from coarse crystalline porphyritic granites. It is almost impossible to distinguish these rocks in the field from gneisses in granitic origin which have intruded at last and the post stage of the Pan-African Orogeny. However, the presences of greenish mineral dwellings rich in sillimanite and brown-black colored orthopyroxene speckles with a dimension of 2-3 mm are the main distinguishing feature of orthopyroxene gneisses. The exposure in Birgi region extends between Birgi and Cevizalanı village. Various textural features are recognized in this unit. Especially, samples that are much darker in color, coarse crystalline, equally sized granoblastic in texture, are rich in orthopyroxene. The primary granites of orthopyroxene gneisses in Tire region are in general porphyritic textured rocks including orthoclase porphyroblasts. In ductile deformed zones widespread retrogradations into blasto mylonites are observed. Intercalations of paragneiss with orthopyroxene that reach several hundreds of meters in dimension are extremely widespread within the gneisses.

The granulite facies mineral assemblage of orthopyroxene gneisses is made up of 'plagioclase + orthoclase + biotite + orthopyroxene + garnet + ilmenite / rutile' (Figure 4f). Orthopyroxenes are in composition of ferric hypersthene (En_{43-47}) (Figure 5a). Formations of garnet corona similar to pelitic granulites are widely observed in gneisses as well. Garnet coronae around biotite are divided into two zones. The inner zone is defined by plentiful quartz inclusions. Non inclusive outer zone is made up of euhedral garnet crystals advancing through plagioclase. Especially in mylonitic zones, the orthopyroxenes in shear zones are completely replaced by fine grained biotite cluster. These retrogradations make the discrimination of granulitic gneisses impossible from post Pan-African gneisses. The extension of sillimanite crystals parallel to shear zones which give rise to retrogradations indicate that these minerals belong to stage at upper amphibolite facies.

Metagabbro / Metanorites is another lithology which belongs to the Pan- African basement. The magmatic texture and mineralogy in these rocks

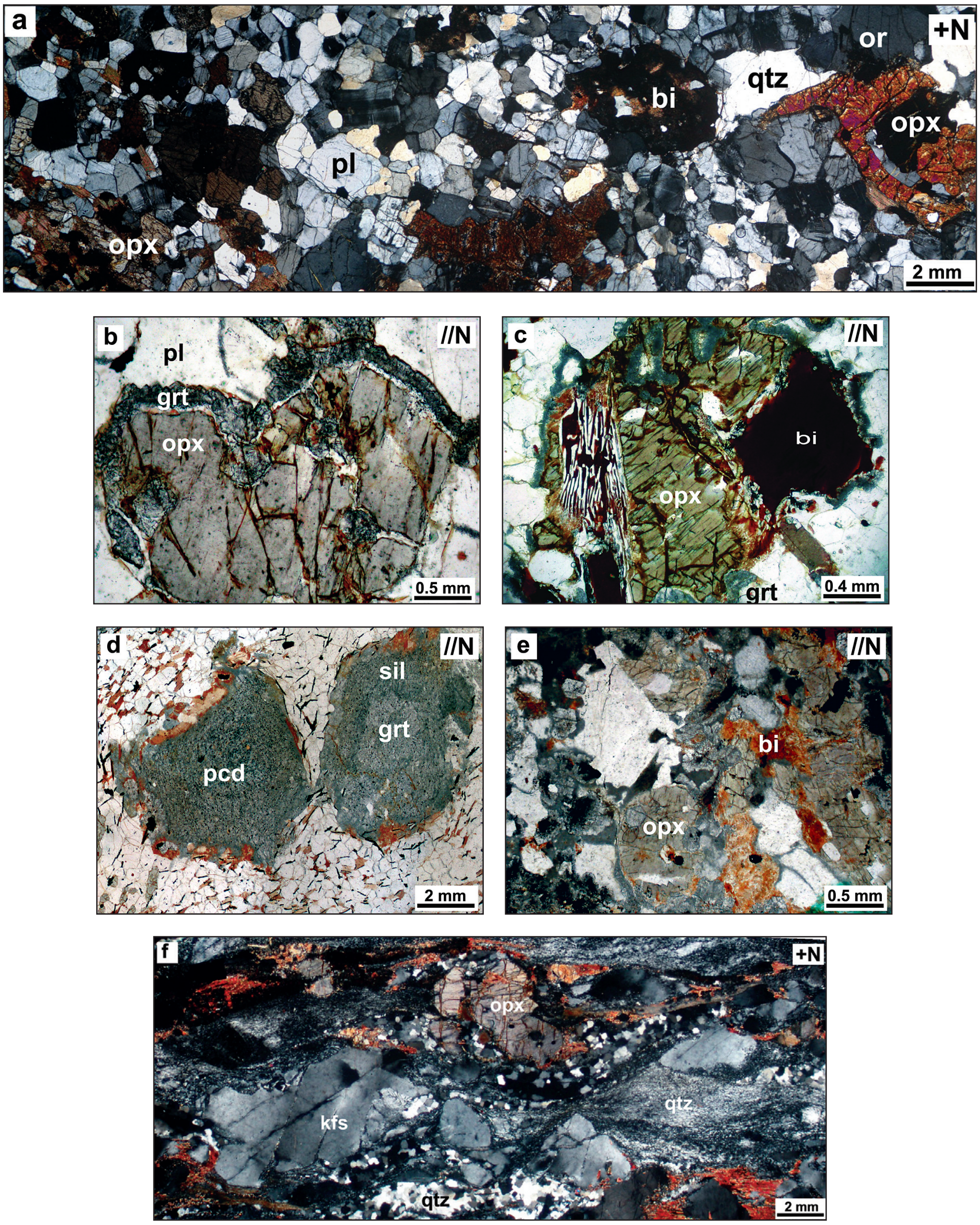

Figure 4- Microscopic views of granulites in the Menderes Massif (Tire / Küre). a: general view of pelitic granulites showing granoblastic polygonal texture and are composed of orthopyroxene, garnet, plagioclase and quartz, b: Garnet rings developing at contacts of orthopyroxene - plagioclase, c: Reaction zones developing at contacts of orthopyroxene - biotite. Orthopyroxenes are consumed by new, small biotites while coarse biotite crystals transforms into biotite - plagioclase symplectic growths, d: Assemblage of sillimanite, garnet, biotite and quartz replacing ?cordierite porphyroblasts belonging to granulite facies (pcd= pseudocordierite), e: the view of fine grained, granoblastic in texture orthopyroxene para-gneisses, f: The mylonitic texture in orthopyroxene gneisses (opx: orthopyroxene, pl: plagioclase, bi: biotite, or: orthoclase, qtz: quartz, grt: garnet, sil: sillimanite, kfs: K- feldspar).

are extremely well preserved and it is macroscopically impossible to examine the granulite facies evidences. Multi ring corona structures that developed at contacts of plagioclase / olivine were interpreted as the effects of granulite facies metamorphism over these rocks (Candan, 1995). The inner ring developing into olivine in these formations is made up of orthopyroxene. However, the outer ring advancing into plagioclase is formed by the spinal - hornblende symplectic growth. In some samples partial garnet ring can also develop at the outermost.

Pressure - temperature conditions

Miscellaneous lithologies in the Pan-African basement include ensembles of similar granulite facies. Classical geothermobarometric calibrations were applied in these ensembles. The geothermometer based on the Fe-Mg change between garnet / orthopyroxene suggested by Lal (1993) gave an average temperature of 730± 20 °C for pelitic granulites (Candan et al., 1998; Dora et al., 2001). Applying of the same geothermometer to orthopyroxene paragneisses around Çine an average temperature of 756 °C has been estimated. 12 different calibrations were applied to biotite - garnet pairs in same rocks. These estimations have shown similarity with values obtained from garnet / orthopyroxene pairs giving an average temperature of 714°C. During assumptions of pressure conditions of the granulite facies metamorphism, the calibration suggested by Newton and Perkins (1982) was used based on the 'garnet + plagioclase + orthopyroxene + quartz' ensembles. This geobarometer gave a pressure value of 6.1 kbar.

The age of metamorphism

The preliminary attitudes regarding the relative age of granulite facies metamorphism affecting the Pan-African basement have been based on the basic geological properties of the Massif (Candan, 1995). Granulite facies metamorphism was interpreted as a probable Precambrian / Cambrian aged event based on data such as; 1- The observation of the evidences related to this metamorphism only in some units that belong to Pan-African basement, and the case that the degree of metamorphism in cover series has not reached to this level in any place. 2- Retrogradation of the ensembles related to granulite and eclogites by an overlying metamorphism under the conditions of upper amphibolite facies most probably associated with widespread migmatization observed in the basement series of the Massif. 3- It has been interpreted that the granulite metamorphism is an Precambrian/ Cambrian event affected only the core series of the massif by basing on the lackness of data approving thet orthogneisses with an average age of 550 Ma intruded at a stage following the Pan-African Orogeny, and contrarily by including the rocks experienced from the granulite metamorphism as intercalations (Candan, 1995; Candan and Dora, 1998).

The first study to determine the age of high temperature metamorphism by radiometric methods has been made on gneisses with orthopyroxene belonging to granulite facies which was observed in Birgi region. U, Th and Pb concentrations of monozites which were picked over this rock were estimated by EMS and the metamorphism age was determined as 660 +61/-63 Ma (Oelsner et al., 1997; Warkus et al., 1998). Although there is a big error range in the estimation this dating is important as this is compatible with the suggested Pan-African age based on the basic geological data. In recent years, zircon was picked ovre pelitic granulites in Tire region and ion micro probe (SHRIMP II) method was applied to these in order to detect the age of this metamorphism (Koralay et al., 2006). Cathodoluminescence (CL) photos of zircons picked over these granulites showed that unzoned zircon overgrowths belonging to granulite facies are surrounded by planar zoned outer zones indicating crystallization from an anatectic melt. The U-Pb ion microprobe (SHRIMP II) analysis of unzoned overgrowths were clustered at 583.0±5.7 Ma and this late Neoproterozoic age has been interpreted as new zircon overgrowths occurred during the granulite facies metamorphism related with the Pan-African Orogeny (Koralay et al., 2006).

ECLOGITE FACIES METAMORPHISM

Petrography and Mineralogy

The basic properties of high pressure metamorphism affecting the Pan-African basement of the Menderes Massif have been established by studies that have continued nearly 15 years (Candan, 1994, 1996*a-b*; Candan and Dora, 1998; Candan et al., 1994, 2001; Oberhänsli et al., 1997, 1998). Field and petrographical/petrological data have shown that high pressure metamorphism rocks within the Pan-African basement of the Massif could be evaluated in two groups. These are; 1- Eclogitic metagabbro in which relic texture and phases could be observed belonging to uncompleted reactions and primary magmatism that are closely associated with metagabbros, and 2- Eclogites that do not bear relic texture and mineral related to protoliths and fully recrystallized.

The eclogitic metagabbros has been determined in more than 30 locations in the northern and central submassives of the Massif (Figure 1). However, almost no data have been obtained from Çine submassif. The most typical and well preserved outcrops are observed in the southeast of Tire, around Küre village (Figure 3), west of Birgi, and around Keşat region. There is a metagabbro stock in Keşat region which has intruded into orthogneiss with a dimension of 1.5x0.4 km. This stock is surrounded by a garnet amphibolite circumference zone not exceeding 20 m of thickness. In many locations within amphibolites, anhedral, partly preserved eclogitic metagabbro relics with dimensions varying in between 20-30 cm to 10-15 cm are present. In addition to these, relic high pressure rocks are frequently recognized in internal shear zones which cut metagabbro. The transformation of gabbro-coronitic metagabbro-eclogitic metagabbro occurs in intermediate areas characterized by low stress. In these intermediate zones primary magmatic phases are statically replaced by high pressure minerals in a way to preserve the original texture (Figure 6a). The tectonic slice in Tire/Küre region where the best preserved exposures of granulites in the Massif are observed, includes numerous metagabbro / metanorite stocks. Many of these stocks are surrounded by partly developed amphibolite zones. The width of eclogitic metagabbro zones exceed 30 m in the region where gabbro-eclogitic metagabbro-garnet amphibolite transformations could be observed with all textural / mineralogical intermediate terms belonging to prograding and retrograding metamorphisms. Even in eclogitic metagabbro samples that have been metamorphosed at the highest grade, there could still be observed relic magmatic phases. Eclogitic metagabbro- garnet amphibolite metamorphisms follow the late stage shear zones which are more effective especially at the outermost parts of masses. Apart from these regions, it was determined that gabbroic stock and vein rocks at south of Alaşehir in Kestane Deresi area and at south of Kula to the north of Yahyaalcı village have been metamorphosed into metagabbros. The eclogitic metagabbro exposure recognized at the northernmost part of the Massif takes place at Simav/south of Beyceköy. In this mass with dimensions of 20 x 5 m located in schists with disthene that show heavy migmatization, the high grade garnet amphibolite metamorphism is observed.

During thin section studies, it has been clearly detected that gabbro-eclogitic gabbro transformation occurred by gradual replacement of plagioclase and augitic clinopyroxene by garnet and omphacite. This transformation begins with a coronitic stage and ends by complete replacement of the phases. The first stage is described by the development of garnet rings located at contacts of clinopyroxene, biotite and ilmenite with plagioclases (Figure 6b). Rings made up of euhedral garnet ensembles progress into plagioclase. There is always observed chemical zoning in garnets that the highest CaO content would be towards plagioclase. While the grossular component would increase from 20% to 22%, the pyrope component would decrease from 28% to 25%. Plagioclases also get a cloudy view by inclusions made up of diffuse clinozoisite and by very rare disthene crystals. Omphacite transformation occurs in two different ways. Especially in areas of low tensile where static recrystallization occurs, the magmatic clinopyroxene would turn into omphacite in a way to preserve its primary crystal form. In this formation, the primary pyroxene show an omphacitic transformation in a way that jadeite component would decrease from outer to inner parts. The jadeite component of Na-pyroxene formed by this mechanism is directly proportional to the amount of reactions formed which is proportional to the consumption amount of plagioclase in gabbro. Clinopyroxenes in the original rock present an augitic composition possessing 1.3% moles of Jd component which contains approximately 0.48% Na_2O. As a result of this transformation, the jadeite component of clinopyroxene possessing Na-Aguite component reaches 10% (Figure 5b). The second type of transformation into omphacite realizes by the replacement of primary clinopyroxene by small mineral assemblage made up of omphacite. This type of polygonal crystals of which the Jadeite component reaches 23% presents a composition varying between Na-augite- omphacite (Figure 5b). In further stages of the transformation into eclogitic metagabbro individual garnet dwellings occur in plagioclases. These minerals are also replaced by the ensemble made up of anhedral garnets in a way to preserve their primary crystal forms (Figure 6c). These garnets possess a homogenous chemical composition and their average composition is 'Alm_{60} - Prp_{14} - $Sps_{1.5}$ - Grs_{24} - $And_{0.5}$'. Even in furthermost stages of the transformation, it is possible to observe relic plagioclases in eclogitic metagabbros.

Eclogites are rarely observed high pressure rocks at the Pan-African Basement. These are medium to fine grained, massive structured and are made up of red single garnet crystals that presents a homogenous dispersion over green groundmass composed of omphacite (Figure 6d). Dimensions of these lens shaped masses vary between 5 - 400 meters and are placed in paragneiss and schist units. Eclogites were recognized in two locations in the Massif. 12 different masses were detected in Kestane Deresi area, at south of Alaşehir. The height of these rocks does not exceed 20 meters and are in the form of lensoidic masses. The masses observed within mica schist unit are in dimensions of 80 x 5 meters and are planar rocks at south of Kiraz, the north of Yenişehir Village. The largest one of the 21 various exposures has a dimension of 400 x 200 meters (Figure 7). The inner sides of the mass are well preserved and are transformed into garnet amphibolites along shear zones of circumferences of the mass (Figure 6e). In this transformation omphacites are consumed by symplectically growing augite-plagioclase ensemble (Figure 6f) and garnets are gnawn by plagioclase rings.

These rocks posses a homogenous composition and are composed of 'omphacite + garnet + ruilte + quartz + clinozoisite + amphibole' (Figure 6g). Needle like omphacite crystals have a jadeitic composition varying between 42-50% and are composed of omphacite (Figure 5b). Euhedral garnet crystals have several inclusions composed of Ca-amphibole that belong to former medium pressure metamorphism stage. Euhedral garnets show definite chemical zoning. While the grossular compound increases from 22% to 25% towards circumference, the pyrope compound decreases from 22% to 16%. Amphiboles in eclogites are texturally in equal with pyroxenes. Na_2O content of these amphiboles vary between 4-5% and are composed of barroicite / magneso-catoporite.

Similar retrogradation textures are exhibited both in eclogites and in eclogitic metagabbros. Omphacites are consumed by the assemblage made up of clinopyroxene (Jd_{14}) and plagioclase (An_{8-11}) which presents symplectic growth. These symplectic growths transform into Ca-amphiboles with magnesium hornblende compositions

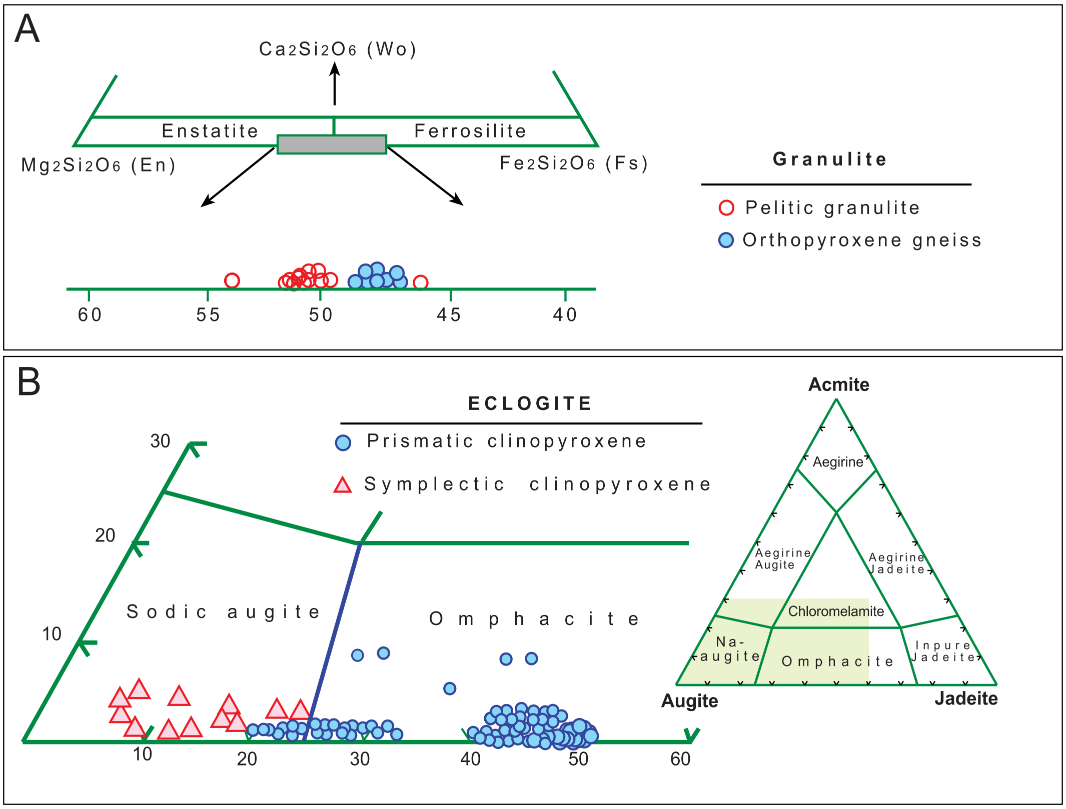

Figure 5- A: The composition of orthopyroxenes observed in granulites (Candan, 1995), B: The compositions of clinopyroxenes observed in eclogites in Essene and Fyfe (1967) diagram (Candan et al., 2001).

in further stages. In addition to these, garnets are surrounded and consumed by coronae made up of plagioclases which describe pressure decrease.

Pressure - temperature conditions

There are many calibrations related to geothermometer based on the Fe^{+2}-Mg change between garnet / clinopyroxene pair and these are widely used in eclogites. Estimations of Krogh (1988) and Ellis and Green (1979) were applied to eclogites in the Massif. Under the assumed 15 kbar pressure, the average temperature of the first eclogite was estimated as 596 °C and the second one was estimated as 644 °C. When the temperature interval of 100 mineral pairs were analyzed it was observed that the calibration of Ellis and Green (1979) gives compatible values clustering around 640-655 °C in temperature. This estimation however gives much dispersed values (±151 C) because of incomplete reactions, relic phases and distinct chemical zonings in eclogitic metagabbros. The estimation of Ellis and Green (1979) gave a temperature value of 633 °C under assumed 12 kbar in pressure.

Reaction of albite = jadeite + quartz which belongs to Holland (1980) is widely used in eclogites for the assumption of pressure. However the pressure values obtained from this calibration are accepted as minimum since albite is not in equilibrium in eclogites. Pressure of 15

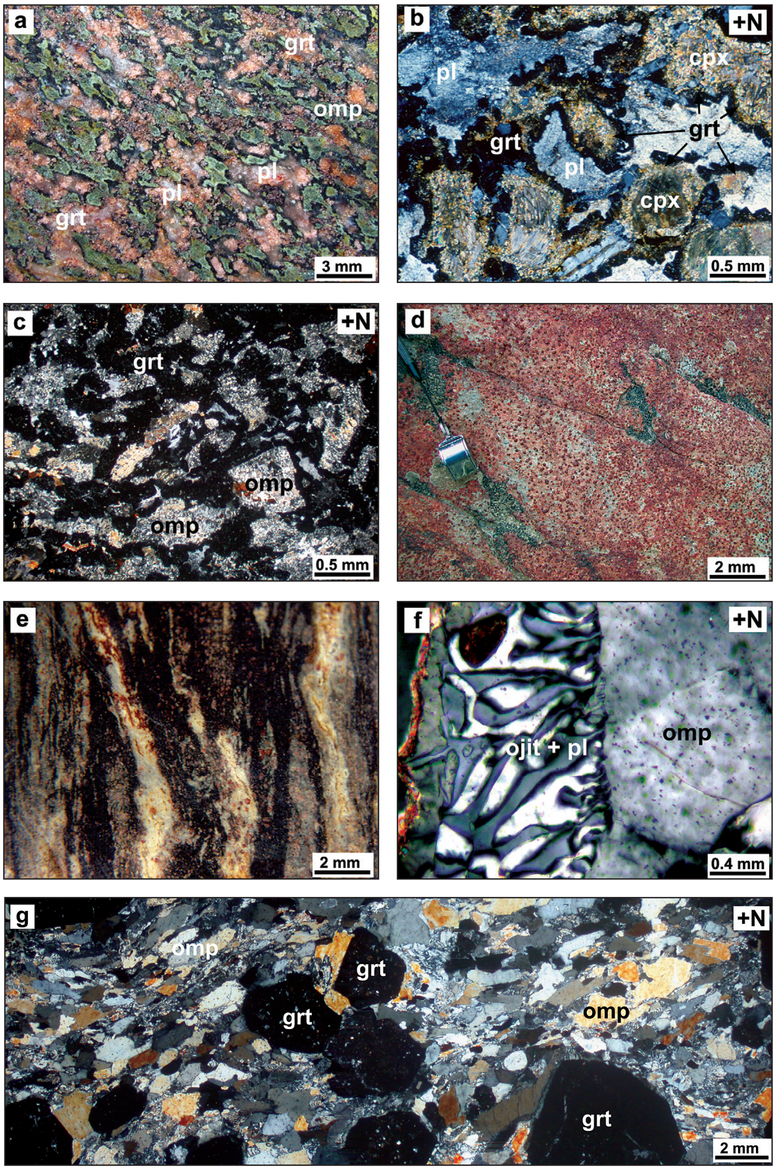

Figure 6- a: Relic texture belonging to primary gabbroic rock in eclogitic metagabbros which were statically recrystallized in low tensile regions. Plagioclases belonging to primary gabbro in rock can be observed, b: the development of garnet corona between primary clinopyroxene and plagioclase illustrating the beginning stage of gabbro - eclogitic metagabbro transformation, c: The relic primary ophitic texture in eclogitic metagabbros. Plagioclases and clinopyroxenes are pseudomorphically replaced by the assemblage of garnet and omphacite. Primary relic plagioclases among garnet ensembles can still be detected, d: Fresh eclogite made up of euhedral garnets within fine grained omphacitic groundmass. Textural / mineralogical evidences belonging to protoliths in fully recrystallized rocks were completely wiped away, e: Eclogite - garnet amphibolite transformations developing along shear zones that belong to retrogradation stage. Dark areas describe garnet amphibolite and light areas describe partly preserved eclogite layers, f: The consumption of omphacite by the symplectic growth augite - plagioclase ensemble, g: The microscopic views of fresh eclogites composed of prismatic omphacite and euhedral garnets (omp: omphacite, grt: garnet, pl: plagioclase, cpx: clinopyroxene, views from A to C belong to Tire / Küre region, from D to G belong to south of Kiraz).

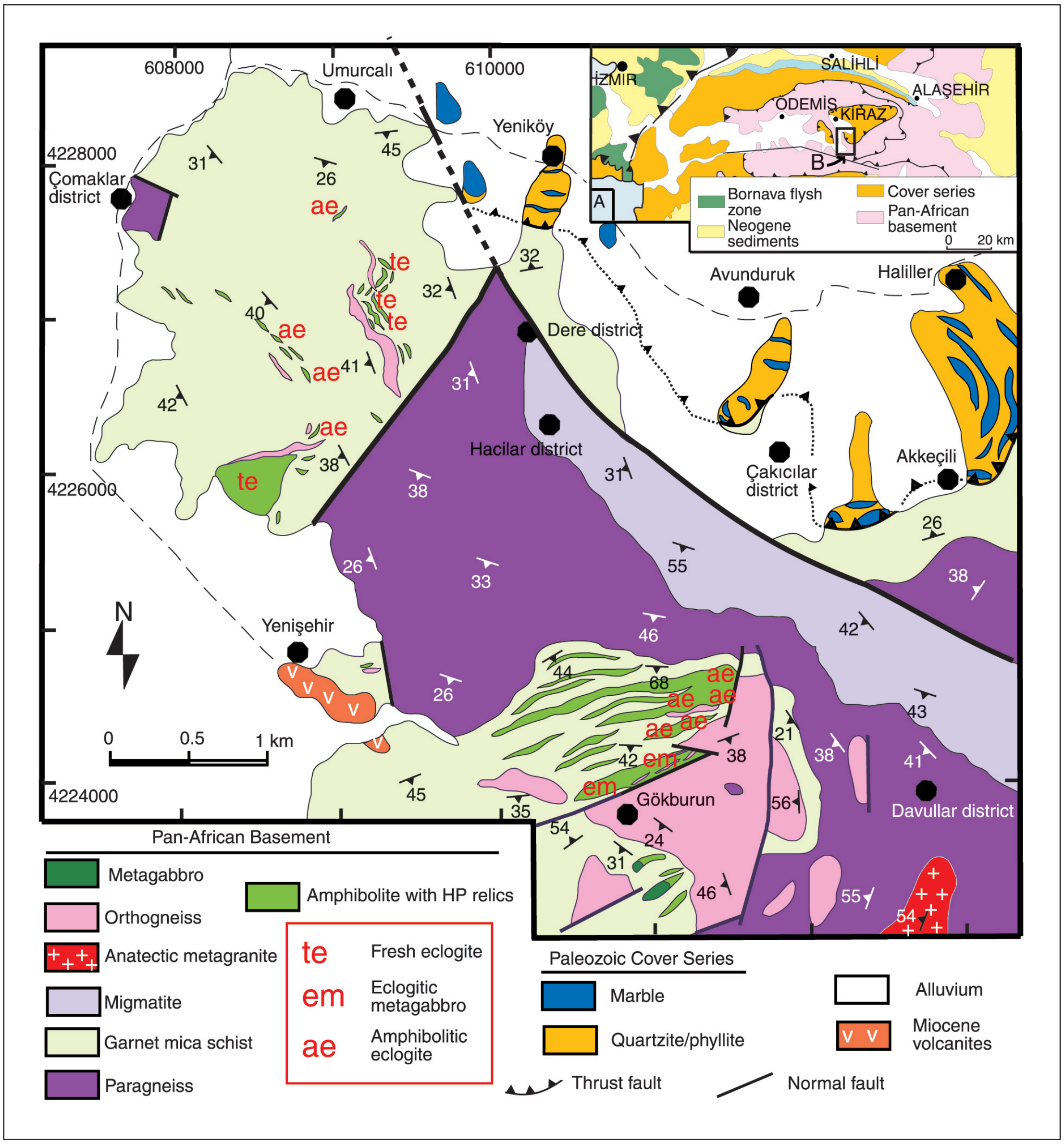

Figure 7- Geological map of Kiraz surround. It is composed of paragneisses that belong to the Pan-African basement, well preserved lens shaped eclogites and metaclastic serial vein made up of comformably overlying schist units (Candan et al., 2001).

kbar has been obtained for the temperature of 630 °C of omphacites in fresh eclogites. The same calibration gave a pressure value of 12 kbar in eclogitic metagabbros.

The age of metamorphism

After determining of the presence of eclogites in the Pan-African basement of the Menderes

Massif (Candan et al., 1994) the suggestions regarding the probable age of this high pressure metamorphism have generally been based on basic geological properties for many years (Oberhänsli et al., 1997; Candan and Dora, 1998; Candan et al., 2001). It was suggested that the high pressure metamorphism is Precambrian / Cambrian in age and can be associated with the Pan-African Orogeny (Oberhänsli et al., 1997; Candan et al., 2001), based on data that; 1- Eclogites are closely associated with gabbro stocks, 2- These gabbros are observed within the Pan African basement, 3- Eclogites are not present in cover series, and 4- Cover series are excluded from textural data although there are excess evidences related to pressure decrease in amphibolites within the basement.

However many attempts have been done for dating eclogites by classical zircon method, no age data can be obtained in them (Warkus, 2001). Oberhänsli et al. (2001), has applied TIMS method to zircons picked up from eclogites and eclogitic metagabbros. No result has been obtained since these are rather smaller than zircons in eclogites and have low uranium content. However, zircons in a sample of eclogitic metagabbro around Birgi region were dated as 529.9±22 Ma ^{206}Pb/ ^{238}U. This age is compatible with the basic geological properties of the Menderes Massif and has been interpreted as the age of high pressure metamorphism of the Massif by investigators.

AMPHIBOLITE FACIES METAMORPHISM

Petrography and mineralogy

To leave aside granulite and eclogites relics, the Pan-African basement of the Menderes Massif is described dominantly by the presence of the ensembles of Barrowian medium pressure metamorphism. A large range extending from the begining of greenschist facies to the development of migmatization - anatectic granite in metamorphic conditions is observed. Schists belonging to the basement widely crop out in Aydın Mountains and Bozdağlar sectors of Ödemiş-Kiraz submassif. The metaclastics in Aydın Mountains in which the lowest grade metamorphics of the Pan-African basement are observed, are composed of biotite schist and mica that is separated from each other by the appearing of isograd of garnet. Garnets are in the form of euhedral crystals not exceeding one or two millimeters. These rocks are composed of 'quartz + plagioclase + biotite + muscovite + garnet' and diffused syn tectonic growths are recognized in these garnets (Figure 8a). The isograd of staurolite and disthene can be observed in regional scale within a schist unit that reaches 6 km in thickness in Bozdağlar (İzdar, 1971). The formation isograd of these minerals can also be detected in Demirci-Gördes Submassif, at south of Demirci (Candan, 1993). Staurolitic porphyroblasts within schists reach a dimension of 5-6 cm in Demirci region. Inclusional arrangements of staurolites indicate a syn tectonic growth in Bozdağlar (Figure 8b). The general mineral composition of schists rich in biotite is 'quartz + albite + biotite + muscovite + garnet + staurolite + rutile'. Disthene is also added to this assemblage as a result of progressing metamorphism. The disthene crystals in disthene - staurolite schists around Demirci region reach a dimension of 7-8 cm (Figure 8c,d). Staurolite in these rocks gradually removes out and passes into disthene schist in 'quartz + albite + biotite + muscovite + garnet + staurolite + rutile' combination. In transition zones 'staurolite + disthene + sillimanite' assemblage can be detected. Sillimanite is diffused especially in paragneisses forming the lowermost part of metaclastic sequence and schists which intercalates with paragneisses. Cordierite and biotites belonging to granulite facies metamorphism in paragneisses are replaced by sillimanite bearing ensembles. This textural data indicate that the development of sillimanite is associated with the medium pressure metamorphism which occurred at the last stage of poly metamorphism.

Dispersive migmatization and anatectic granite development accompany to paragneisses rich in sillimanite (Figure 8e).The best migmatitic exposures in the Menderes Massif are recognized at south of Kula, around Selce village. This migmatitic focus is in dimension of 15 x 5 km and diagonally developed to primary stratigraphy. The transition into migmatite occurs by gradual increases of leucocratic sections within an approximate zone of 200 meters. Ptygmatic, schollen and schlieren structures are the most frequent migmatitic structures observed in the region. Migmatites in the region can also be recognized as inclusions reaching 4-5 km in dimension in orthogneiss masses. The formation of migmatization in Ödemiş-Kiraz submassif can be detected within only one tectonical slice where eclogites and granulite relics are observed. Many migmatitic focal points that are broken apart from each other are present with a dimension not exceeding than 7 - 8 km in dimensions. Anyhow, all migmatitic paragneisses in Çine submassif are in the form of floating inclusions within gigantic orthogneisses. The dimensions of inclusions change from 10 cm to 6 km. At further stages of migmatization, anatectic granites are gradually passed through. Dimensions of granitic masses may reach up to 4 x 5 km. The anatectic granites in the Massif can be divided into two groups based on the places of crystallization. In situ crystallizing granites in these anatectic granites are dispersive in migmatites. In these granites which garnet porphyroblasts are widespreadly observed and made up of poly grained crystals with a dimension of 4-5 cm, have transitional contacts with migmatites which form the country rock (Figure 8f). These are fine to medium grained massive rocks and are composed of 'quartz + plagioclase + orthoclase + biotite + muscovite + garnet (±sillimanite)'. Granites which do not show migmatization and being crystallized as it rises upper layers form the second group. These granites present distinct intrusive contact relationships with surrounding rocks. The most typical exposures belonging to these granites are recognized in Ödemiş - Kiraz submassif, the south of Kiraz. In this region, 6 independent granitic exposures with dimesions of 2 x 3 km have been observed within paragneisses. Anatectic granites are generally in massive character and were transformed into mylonites that show strong lineation and foliation along Alpine age ductile shear bands.

Pressure - temperature conditions

The Pan-African basement of the Menderes Massif is dominantly defined by ensembles of Barrowian type, medium pressure metamorphism. This basement has gained its main structure by Pan-African metamorphism and is overlain by the metamorphism developed during Alpine orogeny. Especially in homogenously composed, low grade schists, it is almost impossible to differentiate the effects of these two metamorphisms from each other. Classical index minerals show that conditions of Pan-African age medium pressure metamorphism has changed from greenschist facies to upper amphibolite facies which the partial melting had occurred. Okay (2001) made temperature estimations in garnet / biotite (Ferry and Spear, 1978) and garnet / hornblende (Graham and Powell, 1984) pairs from garnet schist and garnet amphibolites in Aydın Mountains and pressure estimations from 'garnet + biotite + muscovite + plagioclase' ensemble (Ghent and Stout, 1984). In these classical estimations, the conditions of the lowest graded rocks belonging to the basement have been determined as 530±40 °C in temperature and 8 ± 2 kbar in pressure. According to Bucher and Frey (1994), the first occurrence of staurolite in pelitic rocks defines the beginning of amphibolite facies and expresses a temperature of more than 500 °C. However, Hoschek (1967) suggests a 540 °C temperatures at 4 kbar pressures and 565 °C temperatures for a pressure of 7 kbar for the occurrence of staurolite. In schists of the Massif that do not bear muscovite, the occurrence of sillimanite with the presence of quartz indicates that upper amphibolite conditions have been reached (600 - 650 °C). In order to estimate the conditions of the last stage, Dora et al. (2001), benefited from 'biotite + garnet + sillimanite' ensemble which replaces cordierites

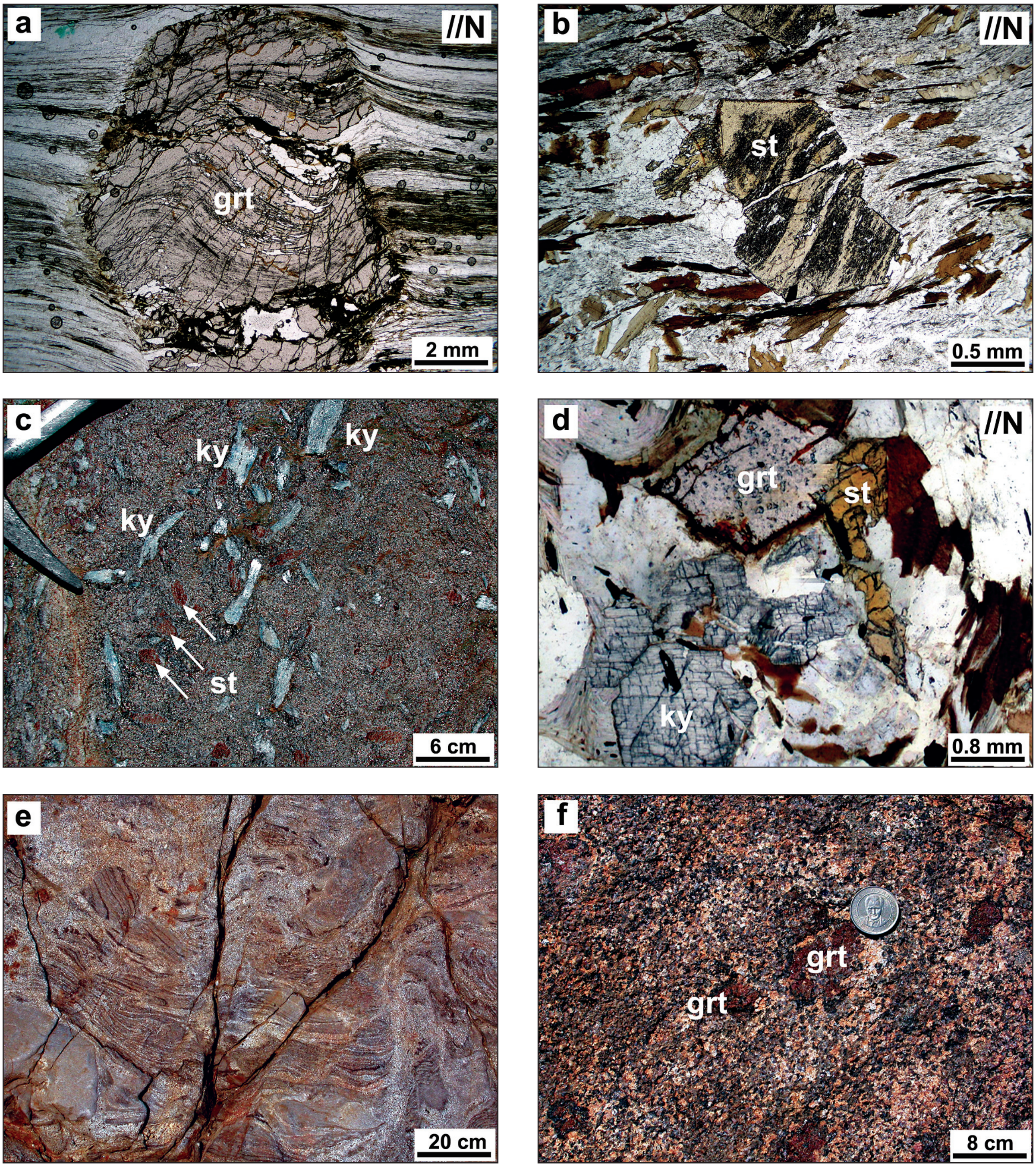

Figure 8- a-b: Syntectonic garnet and staurolite crystals defined by the patterns of quartz + opaque mineral inclusions, c: Staurolite and disthene crystals with dimension of 4- 5 cm which is observed in schists belonging to the Pan-African basement in Demirci region, d: The microscopic view of high graded schists made up of disthene + staurolite + garnet assemblages, e: Widespread migmatization observed in paragneisses cropping out in Selce Village / north of Alaşehir, f: Garnet crystals with dimensions reaching up 4 cm in anatectic granites around Solaklar village / Kiraz (grt: garnet, st: staurolite, ky: disthene).

belonging to granulite facies metamorphism. The temperature of garnet / biotite pairs were estimated at a lower value than assumed (588 °C) as they are fine grained and was affected from retrograde Fe-Mg equilibrium during cooling. It is known that the aforementioned last stage medium pressure metamorphism caused pervasive retrogradations in high pressure metamorphism ensembles at the basement (Candan et al., 2001). An approximate temperature of 623 °C were estimated for garnet / biotite pairs in garnet amphibolites around the wall zones of eclogites based on the calibrations made by Ferry and Spear (1978), Perchuk and Lavrent'eva (1983) and Battacharya et al. (1992). Garnet / hornblende pairs gave also similar temperature values based on Graham and Powel (1984) calibration (approximately 611 °C). 'Garnet + hornblende + plagioclase + quartz' ensemble suggested by Kohn and Spear (1989) were used for the assumption of pressure in garnet amphibolites. This geobarometer gave an approximate pressure of 7.3 kbar (Candan et al., 2001). In addition to these, as described above, pervasive melting in paragneisses at the basement and development of anatectic granite has occurred. This occurrence defines the maximum temperature conditions which the last metamorphic stage affecting the Pan-African basement has reached. In quartz and feldspar bearing rocks, the temperature values of partial melting in water pressure functions are accepted as 650 - 700 °C at water saturated zones (Bucher and Frey, 1994). When classical index minerals and geothermobarometric calculations given above in small amounts are assessed, the conditions of the last stage Barrowian medium pressure metamorphism can be given as 530 - 650 °C in temperature and 7 - 8 kbar in pressure. This last stage metamorphism has affected the Pan-African basement and caused diffuse retrogradations in ensembles belonging to former metamorphisms.

The age of metamorphism

Textural data show that ensembles of granulite and eclogites facies observed at the Pan-African Basement of the Menderes Massif were subjected to retrogradations under the conditions of upper amphibolite facies. Alpine age metamorphism made resetting the isotopic ratios of micas at the basement. Therefore, it seems impossible to designate this high temperature settlement related with the last stage of Pan-African Orogeny by ages of mica. When considered that the Alpine age metamorphism has affected the Pan-African basement as well, especially in schist series those of which have simple in composition, it is extremely difficult to distinguish the effects of the Pan-African and the overlying Alpine from each other. Therefore, to determine the age of the regarding metamorphism by indirect methods might give more realistic results. The most suitable method is to take into consider the migmatites and the associated anatectic granitic development at the basement. Field data shows that migmatization and granite development are restricted to the Pan-African basement. On the other hand, migmatites in question are observed in the form of floating inclusions within low graded and 550 Ma aged orthogneisses. This shows that, the migmatization has occurred before the intrusion of primary granites of orthogneisses and this high temperature can be associated with event causing retrogradation in granulite and eclogites. If this idea is relevant then the migmatization aging could play a critical role to determine the age of the last stage affecting the Pan-African basement.

Geological and petrographical data supports the presence of an original relation between migmatization and the development of anatectic granitic development in the Massif. Such granite observed in Ödemiş-Kiraz submassif, east of Birgi was dated by Hetzel et al. (1998). Zircons which were selected from this granite and thought that crystallized since melting, have been dated as 551±1.4 Ma by classical U/Pb method. On the other hand, age determinations have been made by zircons picked up from neozones of migmatites observed in the middle and in the northern parts of the Menderes Massif

(Dannat and Resichmann, 1998). These zircons were dated in a range between 552 - 502 Ma, averaging at 540 Ma. Investigators have interpreted this age as the crystallizing age of granite associated with partial melting and migmatization in the Massif. When field, textural, petrographical and geochronological data are all assessed, it is understood that the Barrowian type, medium pressure metamorphism representing the last stage in polymetamorphical evolution of the Pan-African basement should be upper late Neoproterozoic (550 - 540 Ma) in age.

THE METAMORPHISM OF THE COVER SERIES

The cover series of the Massif are stratigraphically divided into two sub groups as; 1- Palaeozoic (Upper Devonian (?) - Permo Carboniferous) and 2- Mesozoic - Early Tertiary (Upper Triassic - Eocene) units. Only ensembles of Barrowian type, medium pressure metamorphism are observed in Palaeozoic sequence when metamorphisms of these units are studied. Whereas, although Mesozoic - Early Tertiary sequences are dominantly made up of ensembles of medium pressure metamorphisms, they also contain relic groups of the previous LT/HP metamorphism too.

HIGH PRESSURE METAMORPHISM

Petrography and mineralogy

Data of Alpine high pressure metamorphism (HP) in the Menderes Massif have only been determined in Mesozoic cover series (Rimméle et al., 2003). Mesozoic cover series observed at the southern part of Çine submassif begin with Upper Triassic schists containing quartz and metaconglomeratic layers at the bottom and this unit is transitionally overlain by an Late Triassic-Late Cretaceous aged platform type thick carbonates. Maastrichtian red pelagic marbles indicating the collapse of platform overlies these neritic carbonates and the deposit ends with Paleocene - Eocene aged metaolisthostrom (Özer et al., 2001).

Metaconglomerates emplaced in Upper Triassic clastics has a significant importance in terms of Alpine metamorphism (HP). These quartz metaconglomerates presenting a maximum thickness of 150 meters with a lateral continuity of 3 km, are observed in a few layers (Başarır, 1970). These metaconglomerates are in the character of channel filling which can be traced 150 km from Bafa Lake at the west to Karacasu at the east and made up of a lithology by quartz pebbles and coarse sand with dimension reaching up 6 cm (Figure 9a). Mica rich layers with a thickness of 0.2 - 0.6 m are frequently recognized within conglomerates. These layers have been derived from aluminum rich clays. These clays are rich in rosetta typed, needle like disthene (±chloritoid) crystals in 1 - 1.5 cm (Figure 9b). Quartz veins reaching 20 m in size are presented as contemporaneously with the metamorphism in quartz metaconglomerates. In three locations of the southern part of Çine submassif the presence of carpholite has been detected in these veins (Rimmelé et al., 2003) (Figure 10).

In Selimiye / Kurudere village (the best location), quartz veins are present with dimensions of 20 x 1.5 m within 200 x 100 m quartz metaconglomeratic layers. Green colored fibers with 70 cm in length are observed in these veins (Figure 9c). The fibers which are partly turned into chlorite and made up of carpholite also contain bluish disthene crystals (Figure 9d). Disthenes are pervasively transform into prophyllites in veins where 'Mg - carpholite + disthene + chlorite + quartz' ensemble is observed. Carpholites in the massif are rich in magnesium end member and X_{Mg} ratio varies in between 0.60 - 0.90. Carpholites in Kurudere region are approximately X_{Mg}= 0.68 in composition. However the XMn component is 0.03 approximately. Chlorites are rich in magnesium (X_{Mg}=0.8) and has a composition similar to clinochlor end member. In the second location, the southeast of Yatağan, Bahçeköyü 'Mg - carpholite + chloritoid + sudoite + quartz' assemblage was determined again in quartz veins of

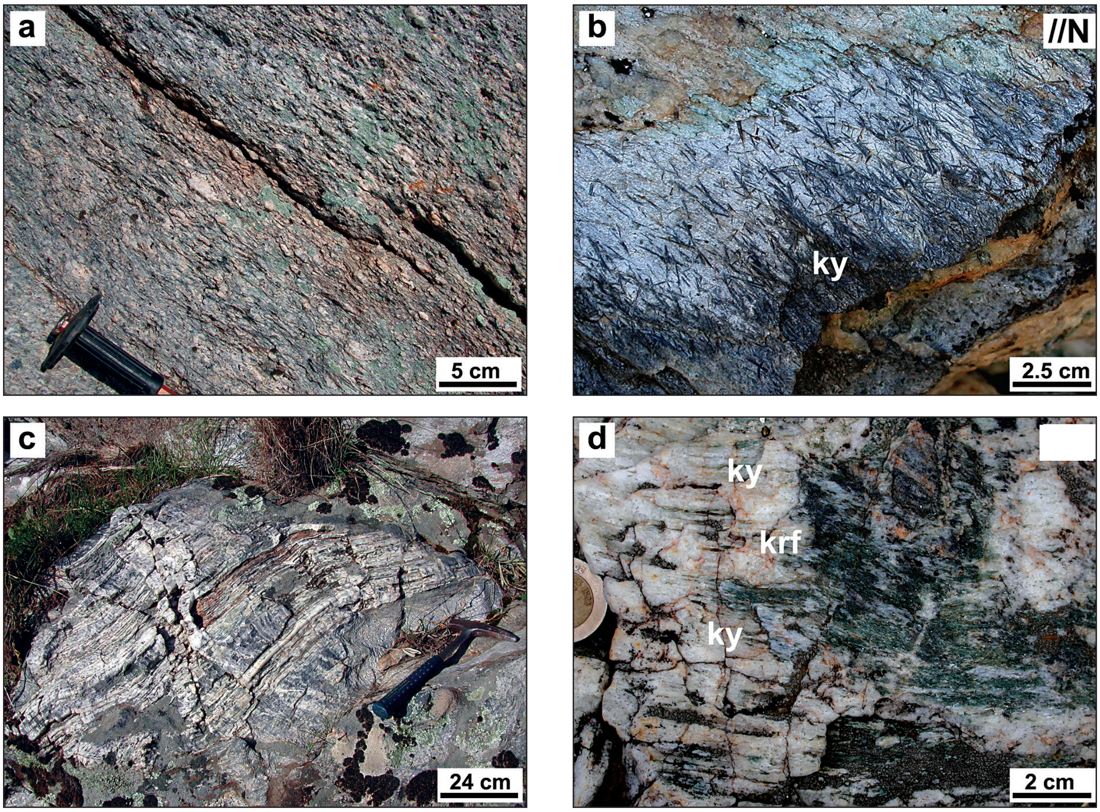

Figure 9- a: Upper Triassic metaconglomerate made up of quartz pebbles and cement of coarse sand, b: Needle like disthene crystals in phyllitic layers transformed from Al rich clays in metaconglomerates, c: Ligament like carpholite crystals reaching up 70 cm in length and observed in quartz veins within conglomerates, d: Green colored prismatic carpholite and blue colored disthene interval observed in quartz veins (krf: Carpholite, ky: disthene, images belong to north of Kurudere village).

quartz metaconglomerates. Carpholites are observed as well preserved in the form of thin fibers in quartz veins. Carpholites in X_{Mg}=0.7 composition are accompanied by phengite, sudoite, pyrophyllite and chloritoid and are rich in manganese (0.15 < X_{Mn} < 0.25) in the region. Textural data indicate that carpholites are the products of transformation of chlorites. Although there is not observed any dishtene in rocks textural evidences in veins show that pyrophyllites were derived from disthene. Chloritoids of X_{Mg}= 0.40 contain 0.40 X_{Mn} end member. In the last location exposed at east of Kavaklıdere, around Nebiler village, 'chloritoid + disthene + chlorite + quartz' and 'pseudocarpholite + disthene + chlorite + quartz' ensemble were detected. Textural data show that carpholites were consumed by the ensemble of 'disthene + chlorite'.

In addition to carpholite development in Triassic conglomerates, Na - amphibole formations have also been detected within Paleocene - Eocene aged metaolistostrome (Kazıklı Formation). Most extensive formation is recognized at west of Denizli / Çal, at Gözdek Hill. Very fine grained, blue colored layers are observed in thicknesses not exceeding 10 - 15 cm in matrix that belongs to olistostrome in this region. In

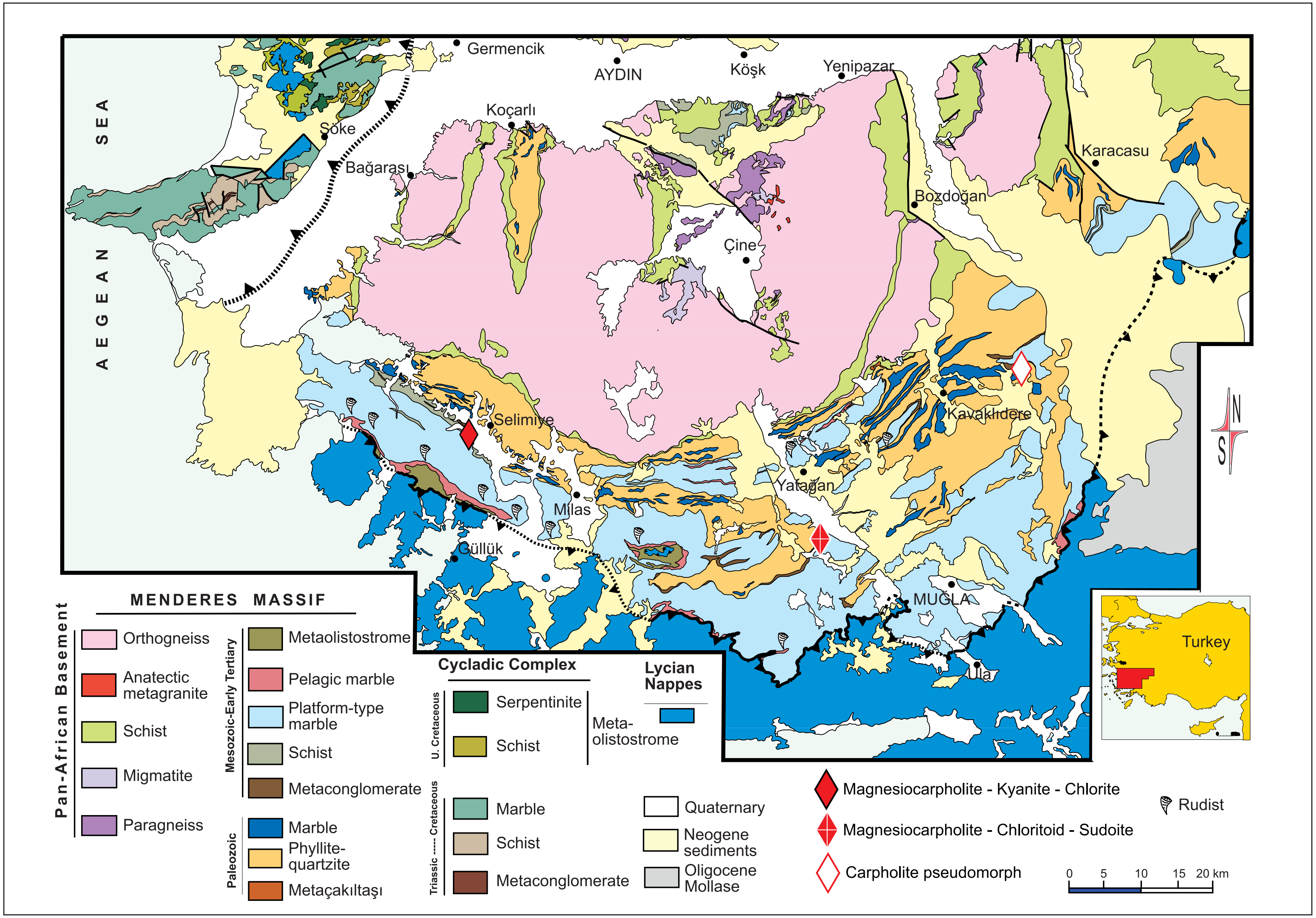

Figure 10- The generalized geological map of the southern part of Çine submassif and locations of Alpine high pressure / low temperature metamorphism ensembles (The map substantially was modified from Çağlayan et al., 1980, locations of rudist belong to Dürr, 1975, Konak et al., 1978 and Özer et al., 2001 and the carpholite locations belong to Rimmelé et al., 2003).

addition to these, similar blue amphiboles were recognized in red pelagic marbles underlying the olistostrome. Al_2O_3 content is less than 2.57 % in these amphiboles and is in Mg - Riebeckite composition.

Pressure - temperature conditions

The P/T (pressure/temperature) conditions of Alpine high pressure metamorphism which affect the Mesozoic sequences of the Menderes Massif have been estimated by PTAX program using the compositions of phases in the region (Rimmelé et al., 2003). Different conditions have been established by the calculations made in three regions where carpholite is observed. The transformation of carpholite into disthene and chlorite and disthene into pyrophyllite define a retrogradation showing isothermal pressure decrease in Kurudere region. Minimum temperature of 430 °C and minimum pressure of 9 kbar were supposed for this retrogradation reaction of carpholite. In the second location (the Bahçekaya region) it was detected that carpholites were replaced by chloritoid. For this region, 440 °C temperature and 4.5 - 6.5 kbar pressure is estimated. The presence of only diaspores in metabauxites around the region shows that retrogradation has occurred in cooler conditions compared to Kurudere. For the 'chloritoid + disthene + chlorite' assemblage in Nebiler region, an average temperature of 450 °C and a pressure of 10-13 kbar is suggested. Consequently, Rimmelé et al. (2003) suggest the condition of this HP metamorphism affecting the Massif as 450 °C in temperature and 10 -12 kbar in pressure.

The age of metamorphism

HP metamorphism in the Massif has not yet radiometrically been dated. Stratigraphical and paleontological data show that the Mesozoic cover series in which HP metamorphism evidences are observed, begins with probable Upper Triassic metaconglomerates and ends with metaolistostrome which the age of it is under discussion (Kazıklı Formation). The Kazıklı Formation which is the uppermost unit of cover series of the Massif was aged as Middle Paleocene by Özer et al. (2001) and as Early Eocene by Konak et al. (1987) in Milas region. In Denizli /Çal region, Early - Middle Eocene age was dated in blocky matrix which overlies red pelagics and is considered most probably as the continuity of metaolistostrome in Milas (Özer et al., 2001). Early Miocene oil shales at the south of Alaşehir are the oldest units discordantly placed on the Menderes Massif. These data show that there has not been any deposition in the Menderes Massif between Eocene - Late Oligocene. Few isotopic age data regarding Alpine metamorphism show compatibility with related time interval. Rb/Sr analysis in white micas were dated in between 63 - 48 Ma with an average of 56 ±1 Ma (Late Paleocene). These ages are interpreted as the crystallization age of Alpine metamorphism. 37±1 Ma Rb/Sr values obtained from biotites are accepted as the cooling age (Satır and Friedrichsen, 1986). New Rb/Sr and Ar/Ar ages obtained from micas show a correspondence with old data. It is considered that Rb/Sr mica ages varying between 62 - 43 Ma (Paleocene - Early Eocene) define the following stage of Barrowian type Alpine metamorphism and 36±2 Ma (Middle Eocene) Ar/Ar ages state the cooling stage (Bozkurt and Satır, 2000). Similarly, Ar/Ar muscovite ages varying in between 43 - 37 Ma (Eocene: Hetzel and Reischmann, 1996) and 36±2 Ma (Middle Eocene: Lips et al., 2001) are interpreted as the cooling age by investigators. On the other hand, it is claimed that the main stage during the passage of Lycian nappes from north to south has occurred between Paleocene - Eocene time interval and this event has continued until Miocene (Collins and Robertson, 1999). It is accepted that the Massif has been buried under Lycian nappes during this tectonical period (Şengör et al., 1984; Dora et al., 1990, Bozkurt and Park, 1999; Rimmelé et al., 2003). When the age of youngest units in the Massif, the oldest sedimentary rocks which cover metamorphic rocks, the available geochronological data and time of passage of Lycian nappes to the south are all assessed together, it can be concluded that the Alpine aged high pressure metamorphism in the Massif and the overlap that caused retrogradation on these communities should occur in Eocene - Oligocene time interval.

MEDIUM PRESSURE METAMORPHISM

Petrography and mineralogy

As explained above, while Mesozoic - Early Tertiary sequences of the Menderes Massif have evidences regarding an overlap under conditions of Alpine aged high pressure and greenschist facies, the Palaeozoic cover series are only made up of assemblages of Barrowian type medium pressure metamorphism. The Palaeozoic cover series of the Menderes Massif has a stratigraphy of Upper Devonian quartzite and conformably and transitionally overlying Permo-Carboniferous phyllite - marble - quartzite intercalation. It has been known for many years that low graded marbles intercalated with phyllites are rich in fossils that have Permo-Carboniferous age in the Massif, in Göktepe region / the north of Muğla, Denizli / south of Babadağ and in Aydın Paşa Valley (Figure 11a) (Çağlayan et al., 1980; Konak et al., 1987; Okay, 2001; Erdoğan and Güngör, 2004). Coral fossils in these marbles have been elongated and flattened as a result of ductile deformation (Figure 11 b). Quartzites derived from pure quartz arenite posses a simple mineral composition and made up of 'muscovite + quartz + apatite + zircon'. As for the black phyllites, that present a diffusion in very large areas in the Massif are rich in index minerals as total rock composites are suitable. At the southern part of the Çine submassif, mineral assemblages reflecting the conditions of greenschist facies are observed along a line extending from Bafa Lake to Denizli. Chloritic phyllites form the most dominant phyllitic type. These fine grained rocks are made up of 'muscovite + quartz + chlorite + opaque minerals'. Garnet phyllites and chloritoid - garnet phyllites are the other dominant phyllitic types. The lengths of the garnet porphyroblasts forming the 50 - 60 % of the rock may reach up to 1 cm. Euhedral garnets posses a composition rich in almandine. Chloritoids are in the form of dark green / black speckles and generally do not exceed 2 mm. The general mineral composition of these rocks is 'muscovite + chlorite + chloritoid + garnet + quartz'. Especially in phyllites around Karıncalı Mountain, the west of Karacasu, 'disthene + chloritoid' intercalation is pervasively observed (Figure 11c). Bow tie and rosetta shaped disthenes with 4 - 5 cm in length are completely in black as these are very rich in graphitic inclusions. Chloritoids could similarly form bow tie - bundle shaped crystals in 2 - 3 cm lengths. The general mineralogical compositions of these rocks are 'muscovite + chlorite + quartz + biotite + disthene + chloritoid + graphite'.

Palaeozoic age phyllites in Ödemiş - Kiraz submassif are observed in two different tectonical slices. Phyllites in the lower tectonical slice make approximately 60 km lateral extension at the south of Aydın Mountains and at the north of Bozdağlar. The Palaeozoic deposit in Aydın Mountains is dominantly made up of phyllites and in these, black marble bands and quartzite layers are observed that have several km's in lateral. Phyllites are composed of biotite phyllite and chlorite (±chloritoid). The Palaeozoic sequences in Bozdağlar are dominant in phyllites and strongly show isoclinal foldings. This folding has a strike of N30°E and cause the repeating of the staurolitic isograd several times. Chloritoid phyllite and staurolite - garnet phyllites are observed in the region. Chloritoid phyllites are fine grained rocks and composed of 'muscovite + chlorite + biotite + chloritoid + quartz' (Figure 11d). With a transition zone where 'chloritoid + staurolite' assemblage (Figure 11 e) in the equilibrium is observed passes through staurolite - garnet phyllites. The staurolitic crystals in these rocks are needle like and 3 to 4 mm in length. Garnets form 2 to 3 mm in diameter and are euhedral crystals. The general mineralogical composition of these phyllites was defined as 'muscovite + quartz + biotite + garnet + staurolite'. The most typical characteristic of phyllites observed in the uppermost tectonical slice is the involvement of garnet porphyroblasts in dimensions of 1 -1.5 cm and 70%. Garnets are accompanied by staurolite and disthene crystals in dimensions of 3 - 4 mm (Figure 11f). In garnet porphyroblasts the textural zoning showing multi phase growth is observed that is made up of non inclusive wall zones and syntectonic core. The mineralogical composition of these phyllites is 'muscovite + quartz + garnet + staurolite (±chloritoid, ±disthene). Chloritoids are generally observed in the form of inclusions around cores of garnets. In Ödemiş - Kiraz submassif, the units belonging to Palaeozoic sequences crop out between Kemalpaşa and Salihli. This region is made up of phyllites rich in graphites and bear black marble bands. Phyllites similar to ones in Ödemiş contain 'chloritoid - staurolite - garnet' ensemble.

Pressure and temperature conditions

As also seen above, the presence of mineral assemblages associated with Barrowian type medium pressure metamorphism has been established in the Palaeozoic sequence of the Menderes Massif, so far. Chlorite, chloritoid, biotite and garnet minerals defining the conditions of progressing greenschist facies are pervasively observed in these rocks where exposed in various regions of the Massif. As for the phyllites in Bozdağlar, the presence of 'staurolite - chloritoid' assemblage have been determined. This assemblage is equivalent of passage of greenschist - amphibolite facies which defines a narrow temperature interval (approximately 550 °C) in rocks possessing a special total chemical composition (Bucher and Frey, 1994). The companion of staurolitic disthene at south of Ödemiş and Kula defines the progressing conditions of amphibolite facies. As a summary, the metamorphic conditions of the units petrographically equivalent to Palaeozoic sequences of the Massif present a change extending from lower greenschist facies to middle amphibolite facies.

The pressure/temperature calculations in ensembles of Palaeozoic sequences based on classical geothermobarometric methods have only been made in several locations. Ashword and Evirgen (1984) and Whitney and Bozkurt (2002) benefited from garnet/biotite pairs in Palaeozoic sequence that contains garnet and crops out at the southern part of the Menderes Massif. In these studies temperatures of 550 °C and 500 °C were obtained. In same studies, a pressure of less than 6 kbar was envisaged based on the assumption of the garnet + biotite + muscovite + plagioclase + quartz assemblage. For garnet - chloritoid phyllites in the same region Regnier et al. (2003) similarly suggests a pressure of 4 kbar and a temperature of 525 °C. The calculations in staurolite - garnet - disthene phyllites are a bit high and 8 - 11 kbar / 600 - 650 °C pressure and temperature values have been obtained, respectively. These phyllites are exposed at south of Koçarlı and have mistakenly been added to the Pan-African basement by investigators. Substantially, petrological / petrographical data are compatible to each other and these define an advancing medium pressure metamorphism and are changing from lower greenscihst to middle amphibolite facies.

The age of metamorphism

There is not any direct temporal / spatial evidence related to age of Palaeozoic sequence of the Menderes Massif and with Alpine HP/LT metamorphism observed in Mesozoic - Early Tertiary sequences. There are few cooling ages obtained from micas in units of the Pan-African basement in the Massif (Paleocene - Eocene). The primary contact relationship between Palaeozoic and Mesozoic - Early Tertiary cover series is stratigraphic (Konak et al., 1987). There is not any data associating with the effects of Variscan Orogeny in Anatolides. When all these evidences are evaluated together it is considered that the metamorphism of Palaeozoic sequences should be in Alpine age (Eocene-Oligocene) like Mesozoic - Early Tertiary sequences.

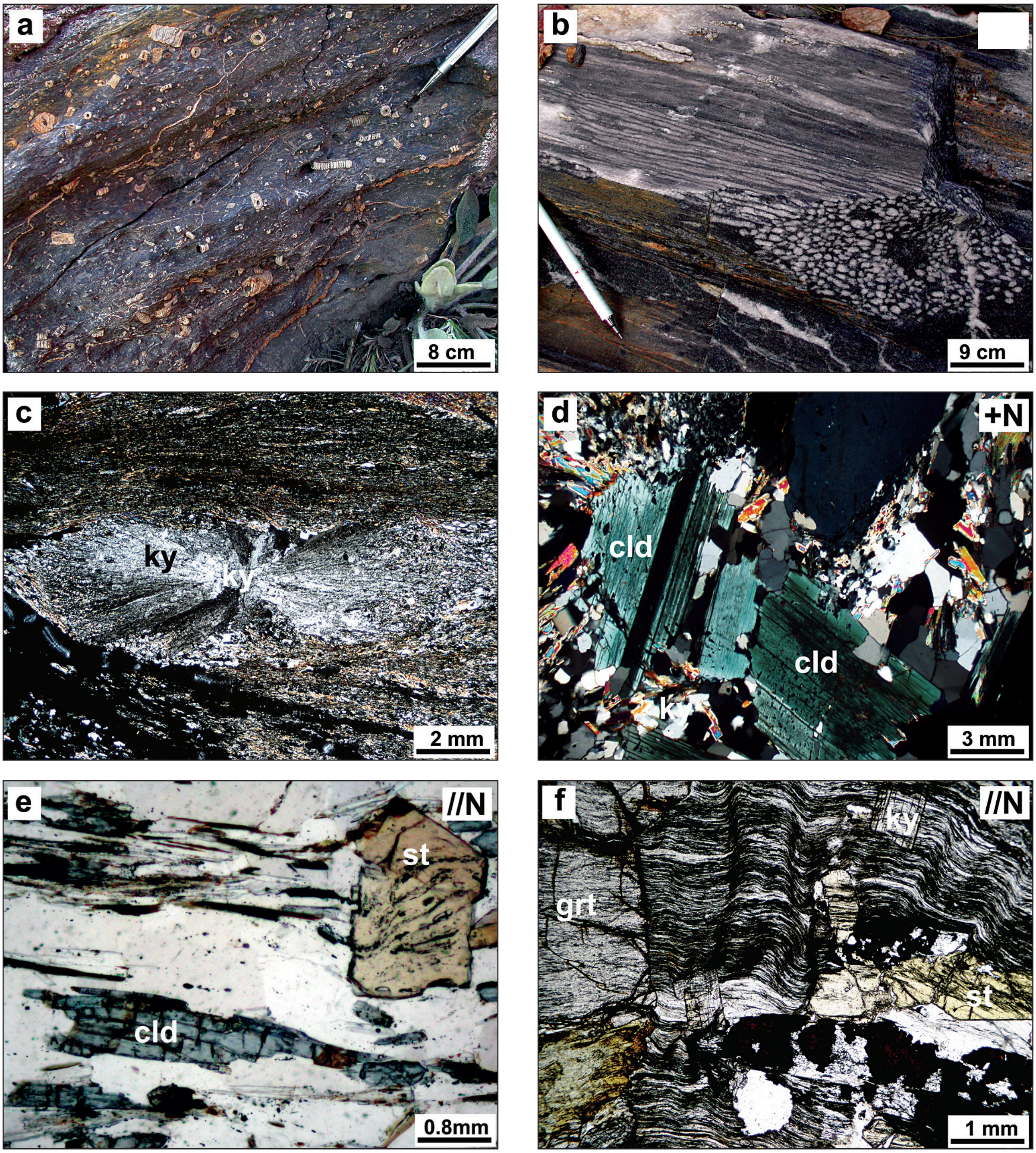

Figure 11- a: Crinoid fossils within black marbles belonging to Palaeozoic cover series in Göktepe / Muğla, b: coral fossils subjected to ductile deformation within black marbles in Karıncalıdağ / Karacasu, c: Disthene crystals growing as bow tie observed in phyllites, Karıncalıdağ / Karacasu. Disthenes are accompanied by small chloritoid crystals (within a mica rich groundmass) of in a way to describe greenschist facies to them, d: Chloritoid phyllites observed in Bozdağlar, e: 'Chloritoid + staurolite' assemblage defining conditions of greenscihst - amphibolite facies transitions in phyllites, f: 'Garnet + staurolite + disthene' assemblage observed in phyllites at south of Kiraz (ky: disthene, cld: chloritoid, st: staurolite, grt: garnet).

DISCUSSION

Before discussing the metamorphic evolution of the Menderes Massif on the basis of core and cover series it will be useful to briefly deal with the opinions made on this subject. These opinions can be divided into two subgroups as i) the single phase Alpine metamorphism that yielded the present metamorphic character of the Massif and ii) the Pan-African and the Alpine age metamorphic evolutions of the base and cover series.

The majority of investigators defending the single phase model base their opinions on studies they have made on the southern part of Çine submassif. Ashword and Evirgen (1984); Erdoğan and Güngör (2004) and Bozkurt (1996); Whitney and Bozkurt (2002) are the chief investigators defending the single phase model in the Menderes Massif. These investigators substantially, accept orthogneisses belonging to basement as Tertiary granites and Pan-African metaclastics as units of cover series. As a result of this, it is defended that there is not an old basement in the Menderes Massif and thus the whole metamorphic evolution of the Massif can be explained only by the Alpine metamorphism.

Contrary to opinions stated above, there has been presented many evidences that the base and cover series of the Menderes Massif has a complex polymetamorphic evolution. Since there have been fewer evidences in radiometric and petrological data different opinions have been suggested about the metamorphic age and conditions of the Pan-African Basement in studies made before 1990. Schuiling (1962) suggests Pre-Hercynian age for the metamorphism of the basement while Brinkmann (1967) and Başarır (1970) accept this event had occurred in Precambrian. In 80's, based on the first age data obtained from gneisses which accumulates around 550 - 500 Ma this metamorphism was dated as Cambrian - Ordovician in age (Dora, 1975; Şengör et al., 1984; Satır and Friedrichsen, 1986; Dora et al., 1990, 1992). Nowadays, it is heavily considered that the age of the poly phase metamorphism of the Pan-African basement is Precambrian and is associated with the Pan-African Orogeny (Şengör et al., 1984; Oberhansli et al., 1997; Candan and Dora, 1998; Candan et al., 2001).

By many investigators, it is accepted that the last metamorphism which affected the Pan-African core and Palaeozoic - Early Tertiary cover series and gave its recent structure is in Alpine age. Because of insufficient paleontological data in previous studies the age of this metamorphism was suggested as Devonian - Mesozoic (Schuiling, 1962); Jurassic (Başarır, 1975) and Liassic (Dora, 1975). Nowadays, it was determined that the depositional age of units of cover series shows continuity up to Eocene (Konak et al., 1987; Özer et al., 2001). Therefore, the age of Alpine metamorphism has shifted to Tertiary. This Alpine metamorphism was dated as Early Eocene - Oligocene (Şengör et al., 1984), Paleocene - Late Eocene (Dora et al., 1990, 1992), Late Cretaceous - Early Eocene (Erdoğan and Güngör, 2004), Eocene (Rimmelé et al., 2003), Early Eocene - Early Oligocene (Bozkurt et al., 1995).

THE METAMORPHISM OF THE PAN-AFRICAN BASEMENT

As briefly stated above, in many of the studies it has been claimed that the core series of the Massif should have been metamorphosed in Precambrian. Şengör et al. (1984), suggested that the metamorphic evolution of the basement could be associated with the Pan-African Orogeny without presenting any detailed data. The first petrological evidences regarding the complex metamorphic history of the Pan- African basement were defined by Candan (1995) and Candan et al. (1994). The high temperature metamorphism in granulite facies defined by the presence of orthopyroxene has rarely been preserved in units of the Pan-African Basement (Çetinkaplan, 1995; Candan, 1995; Candan and Dora, 1998). However, the presence of extremely well preserved eclogite and eclogitic metagabbro which defines the HP (high pressure) metamorphism conditions crop outs in nearly 100 locations throughout the Massif except the Çine submassif (Candan et al., 1994, 2001; Candan and Çetinkaplan, 2001; Candan and Dora, 1998; Oberhänsli et al., 1997, 1998; Çetinkaplan, 1995). These rocks are observed within the metasediments of high graded continental crust and represent an environment of crustal thickening by means of continental collision. The textural data show that HT/HP metamorphisms of the Massif restricted to the Pan-African basement has been overlain by Barrowian type medium pressure metamorphism which is defined by migmatization and anatectic granite development and were subjected to retrogradation. Migmatization and granitic intrusions are restricted to basement units. Thus, the related medium pressure metamorphism should also be evaluated within the metamorphic evolution of the basement.

As described above, the temporal evidences clearly reveal that the Pan - African basement were affected from the metamorphism that had occurred under conditions of granulite, eclogite and upper amphibolite facies. Geological, mineralogical and textural data show that the medium pressure metamorphism defines the last event within this polymetamorphic evolution (Candan and Dora, 1998). However, there has not been obtained any clear evidence regarding the relative ages of granulite and eclogite facies metamorphisms. Candan et al. (2001) established that high pressure ensembles were retrograded under conditions of isothermal pressure decrease. He has obtained these results by pressure / temperature studies made on eclogites and amphibolites of which are the medium pressure retrogradation products. There is not any textural / petrological data defining the temperature increase between the high pressure and the medium pressure metamorphism which causes retrogradation in high pressure. Therefore, investigators suggest that the relative order of metamorphism affecting the Pan- African basement is 'granulite - eclogites - amphibolite'.

Nowadays, it has been started to obtain some data about the absolute ages of related stages. The first evidences regarding the granulite facies have a broad error range (660+61/-63 Ma; Oelsner et al., 1997, Warkus et al., 1998) and is important in a sense that this high pressure event is Precambrian in age that is associated with the metamorphic stage of the basement. Despite that, analysis made on metamorphic zircons in granulites by U-Pb ion microprobe (SHRIMP II) method in recent years gave 583.0±5.7 Ma age cluster around Late Neoproterozoic age (Koralay et al., 2006). In order to date the high pressure metamorphism in the Massif TIMS method was applied to zircons in eclogite and eclogitic metagabbros. By means of zircons in a sample of eclogitic metagabbro, again 529.9±22 Ma $^{206}Pb/^{238}U$ age was obtained associated with the Pan-African event (Oberhänsli et al., 2010). These two age data are compatible with the suggested relative age between granulite - eclogite metamorphisms. As mentioned in previous parts, dating anatectic granites associated with the migmatization seems as the most reliable method which could be used in determining the age of medium pressure metamorphism defining the last stage of polymetamorphic evolution of the basement. So far, the age data has been obtained only from one of these granitic samples. By classical U/Pb method, Hetzel et al. (1998) estimated 551±1.4 Ma crystallization age for zircons in such a type of granite around Birgi region. On the other hand, zircon ages which define the partial melting period taken from Neozones of migmatites vary in between 502 - 552 Ma (average at 540 Ma) (Dannat and Reischmann, 1998). As seen, while the restricted age data obtained from eclogites and anatectic granite / migmatites clearly show the relation of these metamorphisms with the Pan-African Orogeny. It also presents an interfingering with each other within error ranges. Basic geological data show that the migmatization belongs to the last stage in the poly-phase metamorphism. However, it is clear that radiometric data should be increased in order to make the ages of these two events to be more sensitive.

Şengör et al. (1984) suggested that the evolutions of the Menderes Massif at the west and the old basements of the Bitlis Massif at the east could be associated with the Pan-African Orogeny. The Pan-African Orogeny describes poly-phased orogenic chain of events comprising the subduction, collision and suturing periods associated with the assemblage of the Gondwanaland between 950 - 450 Ma (Kröner, 1984). Actually this event is not only restricted to the African continent but also comprises the all phenomena occurred within the Gondwanaland. The vision of separation of East Gondwana (which is made up of Antarctica, Australia, Madagascar, Sri Lanka and India) from the West Gondwana (mainly made up of Africa and South America) by a big ocean called "the Mozambique Ocean" (Daiziel, 1991) in continental distribution in Neoproterozoic is generally accepted by many investigators (Stern, 1994; Wilson et al., 1997). This ocean is as big as the Pacific Ocean and is believed to have formed by the break up of Rodinia super continent 800 - 850 Ma years ago in Mezo Proterozoic time. The closure of this ocean and the collision of East - West Gondwana continents caused an orogenic belt development in NS trend which extends along the Eastern side of the African continent (Figure 12). This belt is named as the Mozambique belt or as the East African Orogeny (Stern, 1994).

There are many thoughts regarding that the final connection of Gondwana Super Continent was formed by the closure of large and small chains of oceans or by one big ocean (Unrug, 1996). On the other hand, the closure of the Mozambique Ocean and the final connection time of East and West Gondwana are in doubt. The Mozambique belt is substantially characterized by the formation of high graded metamorphism and by extensive granulite formation. In general terms, it is claimed that these granulitic formations are associated with the collision of East and West Gondwana Lands and the crustal thickening by the closure of Mozambique Ocean. It is also considered that the determination of granulite facies metamorphism could play a key role in solving the problem of time of assemblage (Stern, 1994). The age of granulite facies metamorphism in this belt is divided into two groups. Generally, granulite ages of the West Gondwana vary between 715-650 Ma. These granulites crop out at large areas in Kenya, Tanzania, Malawi, Sudan and in Mozambique. 710 Ma (Kröner et al., 1987) and 650-710 Ma (Maboko et al., 1989) ages were taken in Sudan and Tanzania, respectively. However, the granulites located on the same line especially in Madagascar, India, Sri Lanka and East Antarctica gives much younger ages varying in between 620-520 Ma (averaging at 550 Ma) (Madagascar: Paquette et al., 1994, 570-580 Ma; India: Collins et al., 2007, 513 Ma; Sri Lanka: Hölzl et al., 1994, 550-610 Ma; East Antarctica: Shiraishi et al., 1994, 550-520 Ma). In addition to these, similar ages of granulite facies metamorphism were also detected in southern Ethiopia as 545 Ma (Ayalew and Gichile, 1990) and 570 - 620 Ma (Key et al., 1989), in Erithrea as 593 Ma (Andersson et al., 2000). This two various age groups are interpreted in different ways. According to Stern (1994), the first group ages indicate the time of maximum thickness of the crust in continental collision period that is; the final assemblage age of the Gondwana. The investigator also interprets younger ages as a second young continent to continent collisional stage or the development of crustal thickening along a collision zone from west to east. However, Wilson et al. (1997) suggest that the granulites that belong to older group in the Mozambique belt might have developed either in deeper parts of arc regions at approaching plate margins or in collisional environments of small continents with island arcs, before the main collision stage. Wilson et al. (1997) claims that the final collision time between East and West Gondwana presents more compatibility with the ages of granulite facies metamorphism between 600 - 550 Ma determined in Madagascar, India, Sri Lanka and Antarctica as suggested by Kröner (1993) and Kröner et al. (1994) as well.

In recent years, the presence of eclogites has been detected describing the high pressure

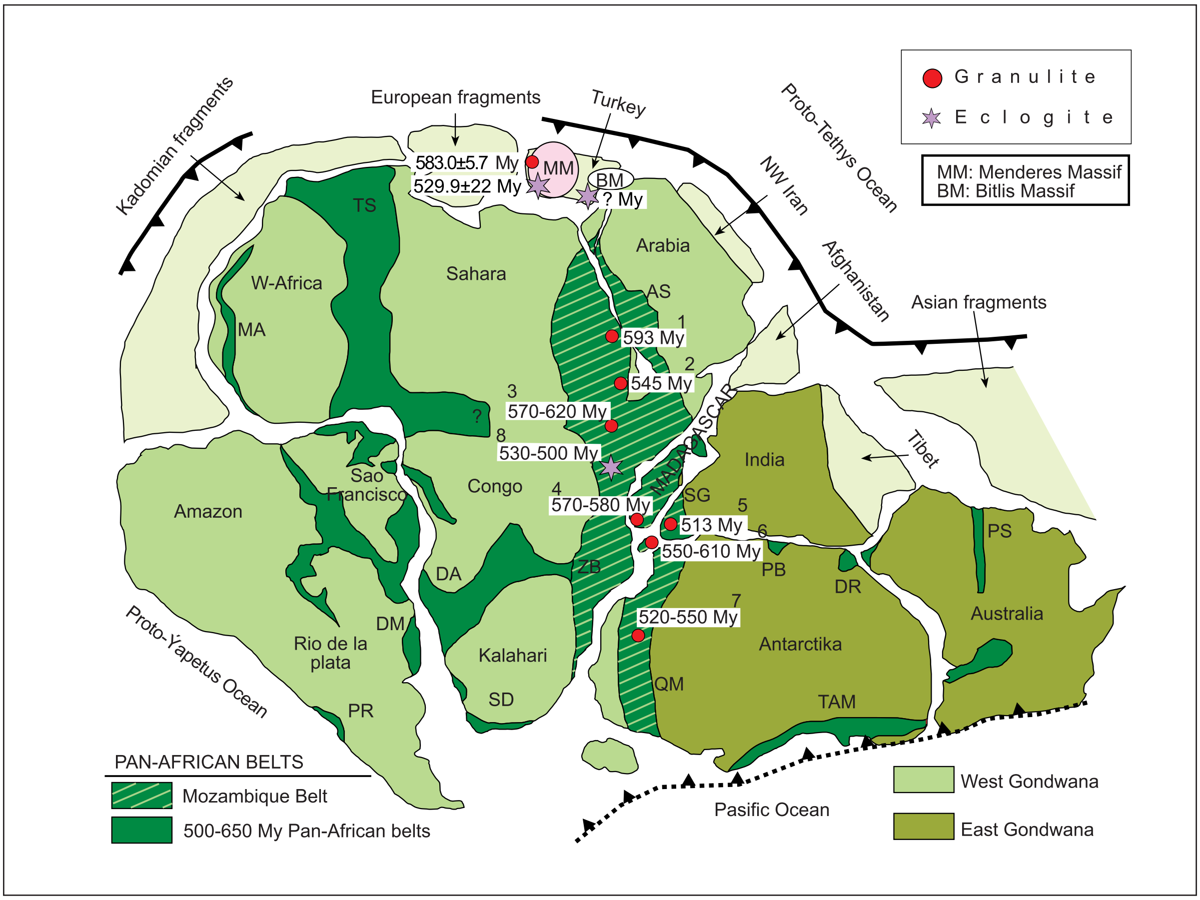

Figure 12- The paleogeographical map of the Gondwana Super Continent in Upper Late Neoproterozoic / Early Cambrian. The Mozambique belt and Late Neoproterozoic - Cambrian aged granulite and eclogite locations are shown on the map (AS: Arabian Shield, BM: Bitlis Massif, DA:Damara, DM:Dom Feliciano, DM:Denman Darling, MA:Mauretanides, MM: Menderes Massif, PB: Pryolz Bay, PP:Pampean Ranges, PS:Paterson, QM:Queen Maud Land, SD:Saldania, SG: South granulite terrane, TAM:Transantarctic Mountains, TS:Trans Sahara belt, ZB:Zambezi, Age determinations were taken from: 1-Andersson et al., 2000, 2-Ayalew and Gichile, 1990, 3-Key et al., 1989, 4-Paquette et al., 1994, 5- Collins et al., 2007, 6- Hölzl et al., 1994, 7- Shiraishi et al., 1994, 8- Ring et al., 2002).

metamorphism under medium temperature conditions in North Malawi located within the Mozambique belt (Ring et al., 2002). These rocks were transformed into high graded garnet amphibolites and are present in the form of lenses and tectonic slice. Zircons selected from these were dated as 530 - 500 Ma according to Pb / Pb method and were interpreted as the age of high pressure metamorphism. Ring et al. (2002) states that these eclogites indicate an environment of crustal thickening that have occurred at subduction and at the following continental collision period. Thus, these eclogites can be used in determining the closure time of Mozambique Ocean. So according to investigators, the collision of East - West Gondwana and the final connection times of the Mozambique Ocean and / or related other oceanic basins are in Cambrian age.

As seen in data given above, the ages of the granulite and eclogite facies metamorphisms within core series of the Menderes Massif show compatibility in temporal and spatial with the periods in the Mozambique belt. On the other hand, the paleogeographical position of Anatolide in Late Neoproterozoic/Early Cambrian is spatially compatible with this metamorphic history. Based on various geological evidences and correlations the western part of Arabian Peninsula is suggested for the position of Anatolia in this period (Şengör et al., 1984; Dora et al., 1995, 2002; Chen et al., 2002; Stampfli and Borel, 2002; Gessner et al., 2004; Gürsu et al., 2004; Monod et al., 2003; Neubauer, 2002; Koralay et al., 2005; Candan et al., 2001; Kröner and Stern, 2005; Oberhänsli et al., 2010). As it is known, Anatolia and the Menderes Massif took place in Alpine - Himalayan belt and were greatly reshaped by the Alpine age deformation and with the associated poly-phase metamorphism. At present, the direct relation between the Menderes Massif and the Mozambique belt has broken by the Alpine deformation. However, the granulite and eclogite ages obtained from the Massif make possible the correlation of the areas in the Pan-African basement like the Menderes and Bitlis massifs (Okay et al., 1985) in Turkey with the Mozambique Ocean. In addition to these, the same data also support that the closure of the Ocean and final collision of East - West Gondwanalands occurred at Precambrian-Cambrian boundary.

Based on the data given above, the tectonic and metamorphic evolution of the Pan-African basement in the Menderes Massif between 600 - 520 Ma time interval can be summarized in main topics as below;

1- Approximately 590 - 580 years ago, the protoliths of paragneiss and schists which are the oldest rocks of the Menderes Massif were deposited. Those are made up of litarenite, subarkose and mudstone and define the environment of passive continental margin (Dora et al., 2001; Koralay et al., 2005). This basin is fed from a provenance composed of crystalline rocks and probably is placed at a location closer to North of Gondwana in the Mozambique Ocean.

2- The closure of the related basin between 580 - 540 Ma time interval within the scope of Pan-African Orogeny caused the development of poly-phase Pan- African Metamorphism. At the first stage of this metamorphic period sediments belonging to core were buried to a depth of 20 km and were metamorphosed under conditions of granulite facies at 730 °C in temperature and 6 kbar in pressure. At this depth, an extra heat source is needed to cause the development of related high temperature metamorphism. It is considered that this heat source is provided from the basaltic magma underlying the crust. The intrusions of gabbro / norite in composition within the Pan-African basement support this idea.

3- In the latter stage of the closure of Mozambique Ocean, the collision of East and West Gondwana caused an excess crustal thicknening and the base rock and gabbros that intruded into were buried to a depth of 50 km. At this stage, the basement was metamorphosed under a temperature of 644 °C and minimum 15 kbar in pressure and gabbro - eclogite transformation occurred in some basic rocks.

4- At stage following the high pressure metamorphism the Pan-African basement got rid of the overlying mass without having a thermal release and was retrograded under Barrowian type medium pressure metamorphism (625 °C / 7 kbar) with a isothermal pressure decrease. This pressure decrease caused diffuse migmatization and development of anatectic granite in rocks.

5- At last stage of the Pan-African Orogeny, 550 Ma in age (Loos and Reischmann, 1999; 570-520 Ma), S type gigantic granite intrusions (protoliths of orthogneisses) occurred by the partial melting of lower crust.

THE METAMORPHISM OF PALAEOZOIC - EARLY TERTIARY COVER SERIES

It will be useful to summarize the most basic geological properties of cover series in the Menderes Massif before discussing the probable tectonic model in order to explain their metamorphisms. These are;

1- The high pressure metamorphism defined by the presence of eclogites within the Pan-African Basement is related with the Pan-African Orogeny and the Alpine metamorphism caused retrogradations only in conditions of lower amphibolite facies on this basement.

2- The Pan-African basement is unconformably overlain by Palaeozoic cover series.

3- Only medium pressure metamorphism related data were observed in Palaeozoic series, so far.

4- There is a stratigraphical primary contact relationship between Palaeozoic and Mesozoic - Early Tertiary sequence.

5- In Mesozoic-Early Tertiary units of cover series data of high pressure metamorphism and medium pressure metamorphism that caused retrogradation were detected.

6- The deposit in cover series continues until Eocene by probable Triassic discordance.

Considering these basic properties, it is needed to discuss the probable reasons of the difference of metamorphism which seem as contradictional between Palaeozoic and Mesozoic - Early Tertiary sequence. The first of these; i) although Palaeozoic sequences were subjected to high pressure metamorphism in Alpine, there is a small probability in the case of not having any related evidence yet. Apart from this, when the presence of disthene and staurolite are considered, it might be thought that Palaeozoic sequences were also affected from Alpine high pressure / low temperature (HP/LT) metamorphism and these assemblages were completely retrograded by the overlying medium pressure metamorphism reaching up lower amphibolite facies conditions. Palaeozoic sequences made up of extremely low graded rocks and bearing only chlorite in regions of the Massif such as Aydın Mountains and Yatağan area do not contain any high pressure metamorphism evidence. Thus, the chance of the first probability abruptly decreases. Another probability is the effect of total rock chemistry on mineral occurrence. It is considered that total Al, K and Na contents of rocks are very effective on carpholite development (Rimmelé et al., 2003). Generally the carpholites are rich in Al and develop in prophyllite and disthene bearing sedimentary rocks and / or in syn metamorphic quartz veins within these sedimentary rocks. The state of being poor in Al or rich in Na-K for rocks obstructs the carpholite formation although there are suitable pressure/ temperature conditions (Rimmelé et al., 2003). Within this scope, it can be considered that phyllites in the Massif are very rich in albite and the carpholite formation in Palaeozoic sequence is obstructed since total rock chemistry is not suitable. Today, there is not any sufficient data to approve which probability is valid. However, there is also another data that could match with available data. In recent studies, the Massif was subjected to strong intra napping during Alpine metamorphism (Konak et al., 1994; Partzsch et al., 1998; Ring et al., 1999; Gökten et al., 2001). The core and cover series of the Menderes Massif were subjected to severe intra napping during collision. Various tectonic slices were buried at different depths and so were metamorphosed under different conditions. All these seem as realistic in probability. In tectonic slices where Palaeozoic sequences are observed, many different degree of metamorphisms are recognized ranging from lower greenschist facies to staurolite - disthene bearing amphibolite facies conditions. Cover series ranging from the Pan-African basement to Tertiary originally overlie each other by stratigraphical contacts. However, many tectonic slices belonging to basement are deprived of data of Mesozoic high pressure metamorphism or Palaeozoic medium pressure metamorphism that reaches the amphibolite facies. All these cases support the second probability.

Another subject that should be discussed is the relative ages of Alpine high pressure and medium pressure metamorphisms. A direct relation between the Alpine medium pressure metamorphism in Palaeozoic sequence and high pressure metamorphism in Mesozoic sequence has not been observed in any places. There are two possibilities in these metamorphisms of which should have periods of tectonical event following the other. If the high pressure metamorphism occurs first, then ensembles associated with this event should have been preserved at low graded layers of the overlying medium pressure metamorphism. If the medium pressure metamorphism occurred first, then it might be considered that the overlying high pressure metamorphism might be effective at low graded layers of the first metamorphism. However, it is not possible to assume that the core and cover series within thicknesses of thousands of meters in the Massif have been buried at the same depth as in one piece during the closure stage of Neothethys Ocean. In case of severe intranapping within the tectonic Alpine evolution of the Massif, it can be considered that each slice has an original metamorphic evolution associated with its burial depth and these have no obligation in resembling each other in character. In conclusion, in order to reach a definite result there is not any sufficient evidence. However, when available geological data are evaluated it is inferred that core and cover series during Alpine tectonometamorphic stage of the Massif were subjected to intranapping. Tectonic slices being formed were buried at various depths and experienced their own metamorphic evolutions and merged together during overlapping.

Within the framework of general tectonical structure of Turkey (Ketin, 1966; Okay et al., 1996), the southern part of the İzmir - Ankara - Erzincan suture zone can be divided into two tectonical units as Anatolides and Taurides. The temporal geological properties of these units which derived from Anatolide - Tauride platform are directly related with the Albian - Eocene stage of the northern branch of Neothethys Ocean (Şengör and Yılmaz, 1981; Okay et al., 2001; Rimmelé et al., 2003; Candan et al., 2005). Anatolides which are the metamorphic equivalents of Taurides are divided into tectonic zones mainly as; Tavşanlı Zone, Afyon Zone, the Menderes Massif and the Lycian nappes from north to south. Under this consideration, the Alpine tectonometamorphic evolution of the Menderes Massif should be deliberated with the evolutions of other zones forming the Anatolides. Two basic properties are observed at common stages of these zones associated with the closure of the Neotethys Ocean. There is a systematic rejuvenation from north to south during the collapse of platform in tectonic zones and the development of pelagic environments and in the high pressure metamorphisms of these zones (Okay et al., 2001; Candan et al., 2005).

Şengör and Yılmaz (1981); Okay et al. (1998) suggest that closure of the northern branch of Neothethys Ocean began in Albian along the intra oceanic subduction zone and the majority of oceanic lithosphere were subducted between Albian - Turonian time intervals (Figure 13 A). The beginning of pelagic carbonate deposition at Tavşanlı zone in Cenomanian shows that the platform began to subside under the load of overlapping oceanic lithosphere progressing southward. At the stage following the subduction of lithospheric mantle, deposits of the passive continental margin were buried under the load made up of oceanic mantle wedge and accretional prism (Figure 13 B). These deposits will later turn into metamorphites of Tavşanlı zone and forms the northern most part of the Anatolide - Tauride platform. The pressure and temperature conditions obtained from Tavşanlı zone (24±3 kbar / 430±30°C; Okay, 2002) and Ar-Ar phengite ages (80±0.5 Ma; Sherlock et al., 1999) indicate that the Tavşanlı zone buried at a depth of minimum 60 km in Campanian and subjected to high pressure metamorphism (Okay et al., 1998, Çetinkaplan et al., 2008). While the neritic carbonate deposition occurred in Turonian - Early Santonian in Afyon zone and the Menderes Massif, the Karaböğürtlen flysch began to deposit in Lycian nappes located at northern parts at that time. The petrological data defined by the presence of carpholite indicate that Lycian nappes were subjected to high pressure / low temperature metamorphism under 8 kbar in pressure and 400 °C in temperature which is equal to a burial depth of 30 km (Oberhänsli et al., 2001; Rimmelé et al., 2005). It is considered that the Lycian nappes were metamorphosed as a result of intranapping of the platform in early Maastrichtian-Early Tertiary (? Early Paleocene) and its burial under the slice of oceanic lithosphere passing southward. The pelagic carbonate deposition in Afyon zone which was derived from the southern part of Anatolide -Tauride platform begins in early Maastrichtian and is overlain by Early Paleocene flysch. The stratigraphical data indicate that intranapped Afyon zone was buried under the Lycian nappes and peridotite slice which passes southward in Middle Paleocene and were subjected to high pressure metamorphism. Metamorphic conditions were determined as 6-9 kbar in pressure and 350 °C in temperature, which equal to a burial depth of 35 km (Candan et al., 2005). The pelagic carbonate depositon in the Menderes Massif forming the southernmost tectonic zone of Anatolides began in late Campanian - late Maastrichtian and this deposition continues with the deposition of Paleocene-Eocene age flysch (Özer et al., 2001). This data shows that ophiolites and Lycian nappes reached this part of the platform. There is a temporal and spatial relation on southward passage between the Alpine metamorphism of the Pan-African basement and cover series of Menderes Massif and Lycian nappes (Şengör et al., 1984; Dora et al., 1990, Bozkurt and Park, 1994, 1999; Rimmelé et al., 2003). The stratigraphical / paleontological evidences and mica ages show that the Barrowian type medium pressure and synchronous high pressure metamorphism are Eocen - Oligocene in age. Palaeozoic and Mesozoic cover series show different metamorphic conditions since Lycian nappes and the platform buried under the overlying peridotite slice were severely intranapped and forming tectonic slices were buried at different depths. For example, pressure of 10 -12 kbar and a temperature of 440 °C values determined for carpholite - disthene ensemble in Triassic metaconglomerates show that some slices were buried at a depth of 35 km. However, slices which were buried at shallower depths were metamorphosed in Barrowian type medium pressure conditions. There has not been any sedimentation on the Massif between Eocene - Late Oligocene time interval. This indicates that the massif was overburden by Lycian nappes in this time interval. Lower Miocene shales are the oldest sedimentary cover on the Massif and indicate that the Massif got rid off the load on it and cropped out at this time (Figure 13 C).

CONCLUSION

The results based on data related to polymetamorphic stages of the Pan- African basement and Palaeozoic - Early Tertiary cover series are given below:

1- The Pan-African basement is defined by the presence of poly metamorphism under high temperature granulite, high pressure eclogites and under the medium pressure upper amphibolite facies conditions.

2- Geochronological data show that these metamorphisms occurred in time intervals of 580 - 540 Ma (Late Neoproterozoic) (granulite facies: 583.0±5.7 Ma; eclogites facies: 529.9±22 Ma; Upper amphibolite facies: 551 - 540 Ma).

3- This poly-metamorphism is associated with the closure of Mozambique Ocean and the collision of East - West Gondwana lands forming the very last stage of assemblage of Gondwana super continent. In this stage the basement was

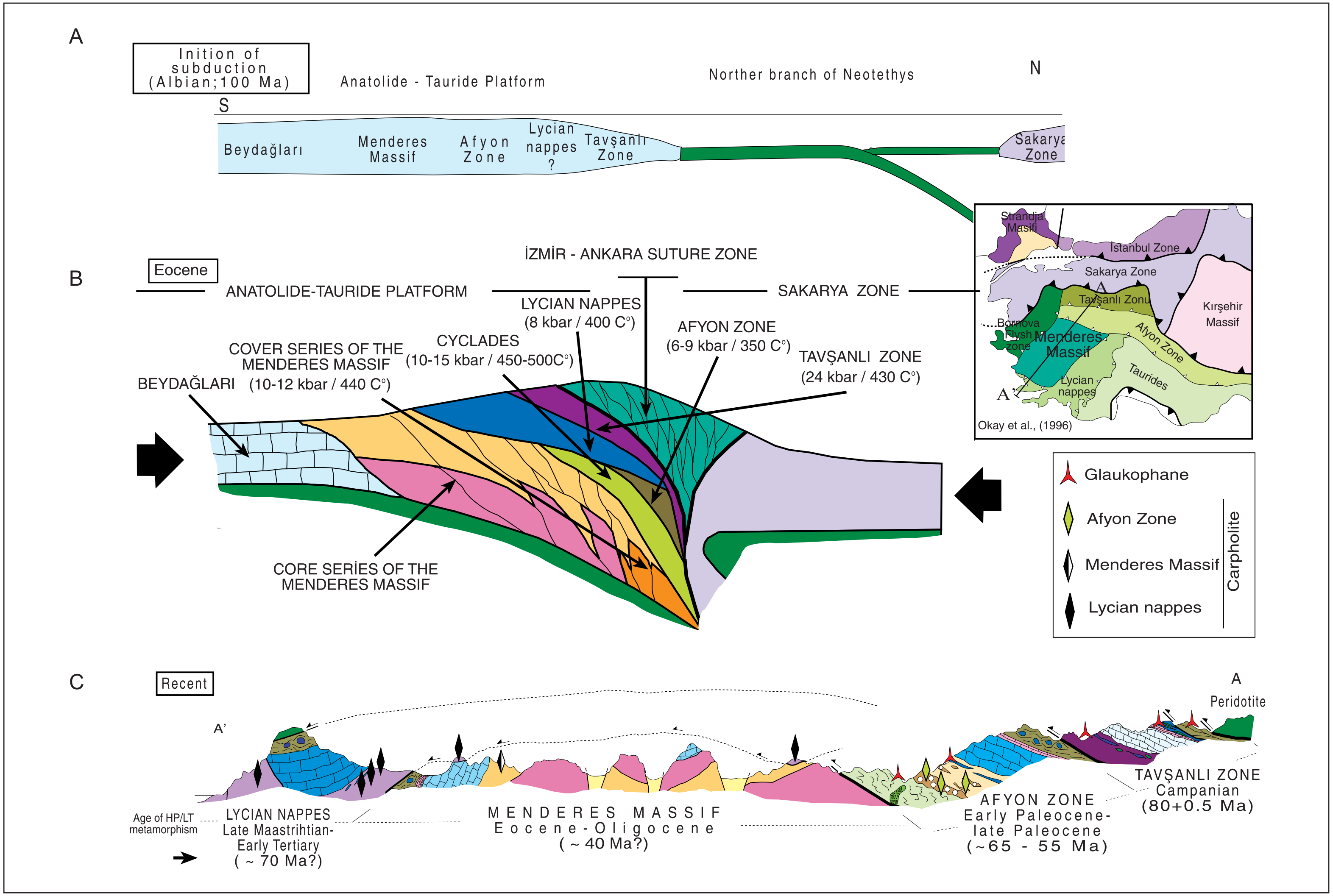

Figure 13- A: the location of Anatolide - Tauride platform and the northern branch of Neothethys Ocean, B: Accretional complex developed on the northern branch of Neothethys Ocean in Eocene. In schematical section, the relative structural positions of HP tectonic zones belonging to Anatolide are shown, C: The geological cross section showing relations of tectonic zones of Anatolides at present (Figures were modified from Rimmelé et al., 2003 and Candan et al., 2005).

subjected to a deep burial and metamorphisms of high temperature and high pressure during overlapping were effectively retrograded under medium pressure conditions.

4- The Alpine metamorphisms of Palaeozoic - Early Tertiary cover series of the Massif are Eocene - Oligocene in age.

5- This metamorphism is associated with the closure of northern branch of Neothehtys Ocean, the continental collision, intranapping of Anatolide - Tauride platform, the burial stage of the part of Menderes massif of the platform below Afyon Zone at the north and the ophiolitic slices of the Lycian nappes passing southward.

6- Some Mesozoic slices were buried at an average depth of 35 km which might cause change in high pressure / low temperature conditions.

7- The effects of Alpine metamorphism in Palaeozoic sequence and the Pan- African Basement dominantly define greenschist facies conditions of Barrowian type medium pressure metamorphism and rarely reach lower amphibolite facies condition.

8- There is not any sufficient data showing if the Pan-African basement and its Palaeozoic sequences were effected from Alpine high pressure metamorphism.

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