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Origin and evolution of the Southeast Anatolian Metamorphic Complex (Turkey)

ÖMER BOZKAYA[1], HÜSEYİN YALÇIN[1], ZEYNEL BAŞIBÜYÜK[1], OLCAY ÖZFIRAT[2] and HÜSEYİN YILMAZ[3]

[1]Cumhuriyet University, Department of Geological Engineering, 58140 Sivas, Turkey; bozkaya@cumhuriyet.edu.tr
[2]Cumhuriyet University, Graduate School of Natural and Applied Sciences, 58140 Sivas, Turkey
[3]Cumhuriyet University, Department of Geophysical Engineering, 58140 Sivas, Turkey

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Abstract: The Southeast Anatolian Metamorphic Complex comprises three structural units, the Keban, Malatya and Pütürge-Bitlis Metamorphics. Of these, the Keban Metamorphics (Carboniferous-Triassic) mainly comprise metamorphosed limestones/marbles and phyllites, consisting mainly of calcite, dolomite, quartz, albite, phyllosilicates (kaolinite, $2M_1$ white K-mica, *1M* biotite, *IIb* chlorite, C-S, C-V and I-S) and scarce tremolite/actinolite and biotite, which were metamorphosed under sub-greenschist- to greenschist-facies conditions. The Malatya Metamorphics (Carboniferous-Triassic) comprise mainly metacarbonate rocks and metapelites — made up of calcite, quartz, albite, phyllosilicates (anchizonal-epizonal $2M_1$ white K-mica and paragonite, *IIb* chlorite, dickite, C-V, C-S, I-S), chloritoid and goethite — that underwent a sub-greenschist-facies metamorphic event. The Pütürge Metamorphics (Precambrian-Permian) comprise metamorphic lithologies of pre-Devonian high-grade (augen gneiss, amphibolite, mica schist/gneiss, granitic gneiss) and post-Carboniferous low-grade rocks (calc-schist/marble and schist). The high-grade parts of this metamorphic unit display a Barrovian-type prograde metamorphism at amphibolite facies. Retrograde mineral occurrences, such as chlorite, C-V and C-S from garnet and biotite, reflect post-metamorphic-peak cooling assemblages. Low-grade parts of this unit are made up of calcite, dolomite, albite, phyllosilicates (*IIb* chlorite, $2M_1$ muscovite and *1M* biotite, C-S), reflecting greenschist-facies metamorphic conditions. Lithological and mineralogical characteristics of the Southeast Anatolian Metamorphic Complex imply the following: the Keban Metamorphics are similar to the Eastern Taurus Autochthon (Geyikdağı Unit) and apparently originated from that unit. In spite of their similar age ranges, the Malatya Metamorphics are quite different from the Keban Metamorphics and were probably derived from northern allochthonous Tauride units (e.g. Aladağ Unit). The Pütürge Metamorphics originated from a southern source (i.e. the Arabian Platform), and horizons of similar age differ from those of the Keban and Malatya Metamorphics.

Key words: X-ray powder diffraction, low-grade metamorphism, petrography, crystallinity, polytype, b_0 value, organic-matter reflectance, phyllosilicate.

Introduction

Southeastern Anatolia is composed of the southeast Anatolian Alpine orogenic segment (with E-W-oriented mountain ranges) in the north and the Arabian Platform with its low-lying plains to the south.

The southeast Anatolian orogenic belt has been divided into three, approximately E-W trending, structural zones (Yılmaz 1993), which are from north to south: (1) a nappe zone, comprising a Late Cretaceous ophiolitic suite and metamorphic units of Paleozoic-early Mesozoic age; (2) an imbricated zone, with imbricated thrust slices of Late Cretaceous–Early Miocene age; and (3) the Arabian Platform (Southeast Anatolian Autochthon), comprising Early Cambrian to Middle Miocene marine sedimentary successions. Southeast Anatolia underwent two major episodes: first, an Alpine deformation with ophiolite emplacement onto the Arabian Platform in the Late Cretaceous; and second, a collision between the northern nappes and the Arabian Plate during the Middle Eocene–Miocene interval. The latter event caused the amalgamation of different tectonic units, namely ophiolitic, metamorphic and volcano-sedimentary sequences (e.g. Şengör & Yılmaz 1981; Yılmaz 1993).

The Southeast Anatolian Metamorphic Complex (SAMC) comprises the main Alpine terranes of the Taurides and the Arabian Plate. The origin and evolution of this complex are important insofar as information collected from it allow reinterpretation of the regional geodynamic scenario, especially concerning the various stages of the Alpine orogeny. Even though these metamorphic rocks carry some clear fingerprints reflecting stratigraphic and mineralogical-petrographical characteristics, there are still various hypotheses — principally two — concerning their origins. In the first hypothesis, the Malatya and Keban Metamorphics represent the Tauride Platform, whereas the Pütürge and Bitlis Metamorphics represent the Arabian Platform (Yazgan 1984; Göncüoğlu & Turhan 1984; Yazgan & Chessex 1991). In the second hypothesis, all of the metamorphic rocks of southeastern Anatolia belong to the Anatolian Platform (Taurides) and display similar stratigraphic successions that were tectonically disrupted and fragmented during the Late Cretaceous (Yılmaz 1993).

The origin of the SAMC has, heretofore, not been definitively determined because its stratigraphic-tectonic aspects were only considered without detailed mineralogical-petrographical studies. However, when the latter aspects are also taken into account, striking conclusions can be reached concerning the origin and tectono-metamorphic evolution of very low- and low-grade metamorphic rocks, as shown by the recent international literature (see e.g. Neubauer & Sassi 1993; Sassi et al. 2004; Kisch et al. 2006; and references therein), and by previous literature on the Tauride Belt (Bozkaya & Yalçın 2000, 2004a,b, 2005; Bozkaya et al. 2002). Accordingly, in this paper, we aim to establish the origin and evolution of the SAMC on the basis of detailed textural and mineralogical properties, such as mineral associations, and the compositions, crystallinities, polytypes and b_0 cell dimensions of phyllosilicate phases.

Geological setting

The northern boundary of the southeast Anatolian orogenic belt is surrounded by the units of the Tauride Belt, an Alpine unit comprising tectonostratigraphic units formed during the closure of the Neotethyan oceanic branch in the eastern Mediterranean region (Şengör & Yılmaz 1981; Göncüoğlu 1997). On the basis of their paleogeographical distributions, the Tauride nappes have been tectonically classified by Özgül (1976) as north- (Bozkır, Bolkardağı, Aladağ) and south- (Antalya and Alanya) derived allochthonous units, and a central autochthonous unit (Geyikdağı) which has been overthrusted by the allochthonous units (Fig. 1a).

The major units in the study area are (Fig. 1b): metamorphic rocks (the Keban, Malatya and Pütürge Metamorphics), the Baskil Magmatics, the Kömürhan Ophiolite and the thick sedimentary successions of southeastern Anatolia. The metamorphic rocks are, from north to south, the Keban and Malatya Metamorphics, previously defined as the Alanya Unit (Özgül 1976) and the Pütürge-Bitlis Metamorphics, previously termed the Misis Unit (Özgül 1976) or Bitlis Zone (Göncüoğlu et al. 1997).

The Carboniferous-Triassic Keban Metamorphics, named by Özgül (1976), crop out near the town of Keban and represent the northernmost metamorphic unit of the Taurides. The northern edge of the Keban Metamorphics was tectonically overthrusted by Mesozoic carbonate rocks of the Munzur Nappes, belonging to the Geyikdağı Unit (Özgül & Turşucu 1984). Upper Cretaceous granitic and syenitic rocks (i.e. the Baskil Magmatics) intruded the Keban Metamorphics along their southern margin (Fig. 1b). Tertiary cover rocks overlie both the Keban Metamorphics and the Baskil magmatic rocks. Although the boundary relations between the Keban and Malatya Metamorphics are unknown, it has been asserted that they have structural and stratigraphic similarities (Yazgan 1984; Yılmaz 1993; Yılmaz et al. 1993). Primary bedding planes of the Keban Metamorphics are generally preserved and these rocks show weak schistosity, whereas the Pütürge Metamorphics display well-defined schistosity. Furthermore, they are intensely folded with NE-trending axes and high-angle dips (>45°), both related to a regional compressional regime.

The Malatya Metamorphics, Carboniferous–Triassic in age (Karaman et al. 1993), have well-exposed tectonic-contact relations with the Paleozoic Pütürge Metamorphics and the Middle Eocene Maden Unit along their southern and eastern margins — a result of southeastward thrusting. East of Doğanşehir, chloritoid-bearing metapelitic rocks of the Malatya Metamorphics have overthrusted staurolite-bearing metapelitic rocks of the Pütürge Metamorphics. These relationships were interpreted as boundaries between lower and upper metamorphic parts of the Malatya Metamorphics (Perinçek & Kozlu 1984; Yılmaz 1993). Farther east, they also overthrust the volcano-sedimentary rocks of the Maden Unit (Fig. 1b). The northern and western boundaries of the metamorphics are unconformably overlain by Eocene and Miocene sedimentary cover units. On the other hand, the Malatya Metamorphics contain abundant NE-SW-oriented mesoscopic folds, indicating thrusting from NW to SE.

The Pütürge Metamorphics, of Precambrian-Permian age, are depositionally overlain by the Maden Unit along their northern edge, whereas they have thrusted boundaries with the Southeast Anatolian Autochthon and ophiolites along their southern and eastern contacts, respectively (Fig. 1b). The metapelites have SW-NE-trending foliations and isoclinal folds with NE-trending axes, reflecting early Alpine stages and a later deformational Alpine stage, respectively. Yazgan & Chessex (1991) pointed out that the first penetrative phase occurred prior to the late Maastrichtian transgression in the Bitlis Massif; thus, the main Alpine metamorphism of the Bitlis–Pütürge Metamorphics may have been related to an ophiolite-obduction event in the Campanian. After the Late Cretaceous, an extensional regime developed in the region, and Middle Eocene sedimentary-volcanic rocks of the Maden Unit were deposited onto the metamorphic and ophiolitic rocks. The metamorphic rocks were thrust southeastward onto Lower Miocene sedimentary units, reflecting the late Alpine period. Therefore, a zone of imbrication developed between the Southeast Anatolian Autochthon and the Bitlis Zone, comprising imbricated thrust slices emplaced onto a Upper Cretaceous-Lower Miocene sequence.

The Baskil Magmatics (Asutay 1987) are exposed extensively around Baskil and Elazığ; these rocks comprise predominantly plutonic (diorite, tonalite, granodiorite), volcanic (basalt, andesite) and volcano-sedimentary (andesitic pyroclastic) rocks and granitic dykes.

The Kömürhan Ophiolite consists mainly of layered cumulates, isotropic gabbros, a dyke complex and a volcanic sequence (Beyarslan & Bingöl 2000), and was thrusted onto the Maden Group and cut by granitic rocks of the Baskil Magmatics.

Materials and methods

A total of 525 metapelitic- and metacarbonate-rock samples were collected from measured sections in the SAMC. The samples were analysed by optical and X-ray powder diffractometric (XRD) methods in the Department of Geological Engineering, Cumhuriyet University, Sivas.

The XRD analyses were performed on a Rigaku X-ray diffractometer (type DMAX IIIC) with the following settings:

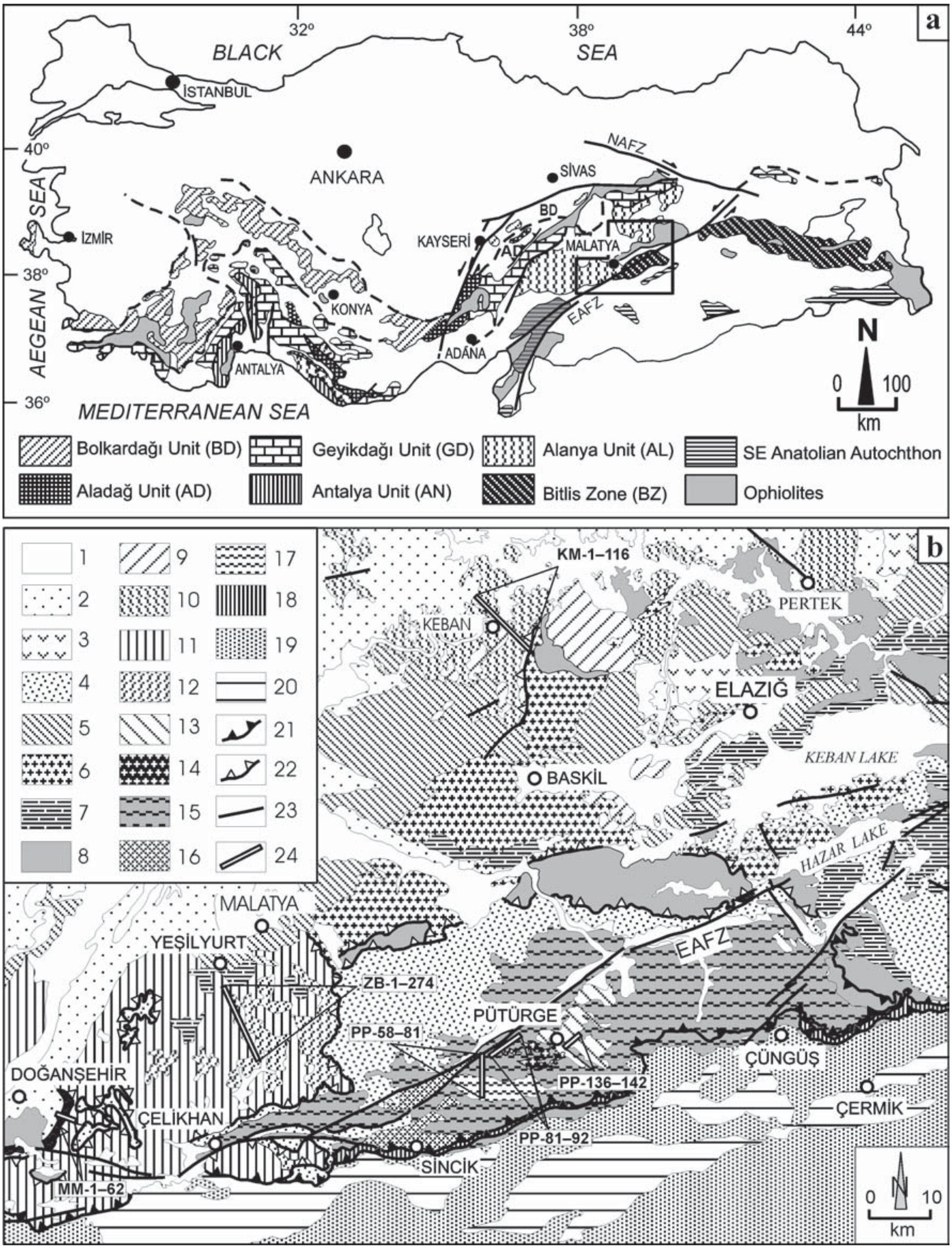

Fig. 1. a — Structural map and distribution of the main Alpine terranes of southern Turkey (modified from Özgül 1976 and Göncüoğlu et al. 1997). **b** — Geological map of the Elazığ-Malatya area (modified from 1:500,000 maps of MTA, 2002). 1 — Pliocene-Quaternary sediments, 2 — Miocene sedimentary rocks, 3 — Miocene volcanic (basalt, andesite) rocks, 4 — Middle Eocene volcano-sedimentary rocks (Maden Group), 5 — Paleocene-Eocene sedimentary rocks, 6 — Late Cretaceous igneous (diorite, tonalite, granodiorite, basalt, andesite, granitic dykes) and pyroclastic rocks (Baskil Unit), 7 — Late Cretaceous sedimentary rocks, 8 — Late Cretaceous ophiolitic rocks (Kömürhan Ophiolite), 9–10 — Keban Metamorphics (9 — Metacarbonates, 10 — Metapelites), 11–12 — Malatya Metamorphics (11 — Metacarbonates, 12 — Metapelites), 13–17 — Pütürge Metamorphics (13 — Metacarbonates, 14 — Granitic gneisses, 15 — Metapelites, 16 — Amphibolites, 17 — Augen gneisses), 18–20 — Southeast Anatolian Autochthon (18 — Eocene-Miocene imbricated sediments, 19 — Cenozoic sedimentary and volcanic (basalt, andesite) rocks, 20 — Mesozoic sedimentary rocks, 21 — Front of Late Miocene Overthrust, 22 — Front of Late Eocene-Miocene Overthrust, 23 — Fault, 24 — Sampling line. EAFZ — East Anatolian Fault Zone, NAFZ — North Anatolian Fault Zone.

CuKα, 35 kV, 15 mA, with slits (divergence = 1°, scatter = 1°, receiving = 0.15 mm, receiving-monochromator = 0.30 mm) and scan speed of 1°2θ/min. Semi-quantitative percentages of whole-rock and clay-fraction samples (<2 µm) from the metamorphic rocks were calculated using multi-component mixtures with the external standard method of Brindley (1980). Patterns of clay-fraction samples (with the samples obtained using the sedimentation method) were acquired under normal (air dried at 25 °C for 16 hours), glycolated (remained in a desiccator at 60 °C for 16 hours) and heated (heated at 490 °C for 4 hours) conditions. Quartz was selected as an internal standard for d-spacing measurements from the clay minerals.

The width of the 1-nm illite and 0.7-nm chlorite peaks at half-height (illite and chlorite 'crystallinity') were measured as Δ°2θ based on the Kübler (Kübler 1968) and Árkai (Árkai 1991; Árkai et al. 1995) indices. The symbols KI and AI were used for illite and chlorite 'crystallinity' as proposed by Guggenheim et al. (2002). For the calibration of the crystallinity measurements, the crystallinity index standards (CIS) supplied by Warr & Rice (1994) were used. A linear regression equation of $KI_{CIS} = 1.1565 \times KI_{CU} - 0.0669$ with $R^2 = 0.9894$ was obtained. All crystallinity values are presented and plotted as recalculated CIS values. Since the 1-nm illite peak for paragonite is broadened asymmetrically towards high angles (Frey 1987), KI values could not be ascertained in samples containing this mineral.

The b_0 cell dimensions — an empirical indicator of pressure (Sassi & Scolari 1974; Guidotti & Sassi 1986; Rieder et al. 1992) — were measured on $d_{060,33\bar{1}}$ reflections using the (211) peak of quartz (2θ = 59.97°, d = 0.1541 nm) as an internal standard. For b_0 determinations, muscovite-rich samples with albite, but lacking or containing only minor amounts of paragonite — that is, the Y assemblage in the AKNa diagram of Guidotti & Sassi (1976) — were evaluated.

Mica, chlorite and kaolin polytypes were determined from diagnostic peaks in non-oriented powder samples, as suggested by Bailey (1988).

The chemical compositions of chlorites were determined by XRD, a valid procedure for chlorite chemistry (Nieto 1997). Al values were determined from d_{001} values, which were measured from d_{005} reflections by using the formula of Brindley (1961). Intensity ratios of the basal peaks of I[(002)+(004)]/I[(001)+(003)], I(002)/I(001) and I(004)/I(003) were used for Fe^{2+} determinations (e.g. Brown & Brindley 1980; Chagnon & Desjardins 1991).

For organic-matter reflectance (OMR) measurements, organic matter was concentrated with HCl and HF acid treatments, and then polished sections were prepared. OMR data were obtained using a Leitz-Wetzlar MPV II-type microscope, a 50× objective, a mercury lamp (CS 100 W-2), a double B12 filter, a B38 heating-absorbing filter, a K510 barrier filter and a point counter at Hacettepe University, Ankara. Sapphire (0.551 % R) and glass (1.23 % R) standards were used in calibration of the microscope, and mean random reflectances (Rm_{oil} %) were obtained using oil.

Petrography

Keban Metamorphics

This unit has four members — lower schist, lower marble, upper schist and upper marble — as subdivided by Asutay et al. (1986). In this study, we prefer the terms of metapelite and metacarbonate to schist and marble insofar as the petrographic determinations on these rocks indicate mainly slate, phyllite and metalimestone and/or metadolomite (Fig. 2).

The lower metapelite member — the lowest part of the Keban Metamorphics — comprises grey-black calc-phyllite, phyllite and calc-schist intercalated with grey-black

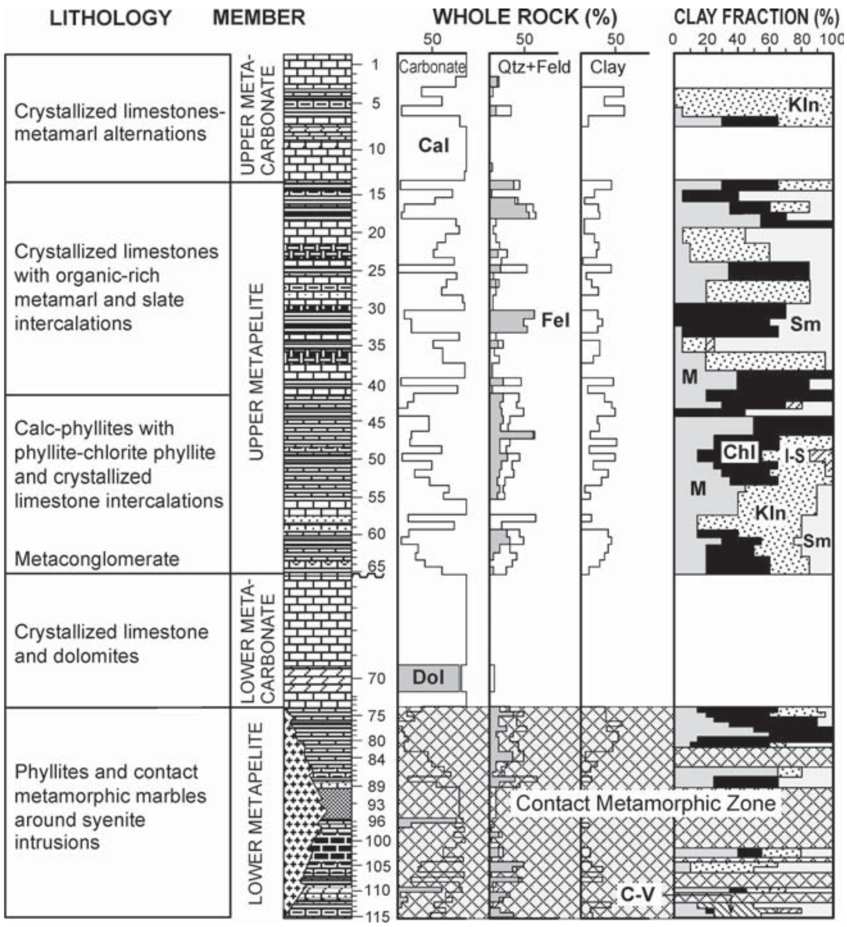

Fig. 2. Vertical distributions of the lithology and mineralogical composition of the Keban Metamorphics (Cal = calcite, Dol = dolomite, Qtz = quartz, Feld = feldspar, Kln = kaolinite, M = K-mica, Chl = chlorite, I-S = mixed-layered illite-smectite, C-V = mixed layered chlorite-vermiculite, Sm = smectite).

metacarbonate rocks, and underwent widespread contact metamorphism — with garnet zones along the margins of syenitic intrusions. Calc-phyllite and scarce quartz-phyllite show typical crenulation cleavage in the phyllosilicate-rich parts (Fig. 3a). Metacarbonate rocks include metalimestone microlaminations (with microgranoblastic texture) and marble (with typical granoblastic texture). Elsewhere, they also contain garnet (andradite), tremolite, albite and epidote, all due to contact metamorphism near the syenitic intrusions.

The lower metacarbonate member comprises grey-black recrystallized limestone and pink dolomites. Intra-dolomicrosparitic layers occur in the lowest levels, and also locally as matrix in the brecciated crystallized limestones.

The upper metapelite member disconformably overlies the lower metacarbonate member; grey-brown metaconglomerates occur at its base, in which pebbles derived from the underlying metacarbonate unit are elongated, with their long axes parallel to the schistosity. Its main lithologies are grey phyllite (calcite-epidote-albite-biotite

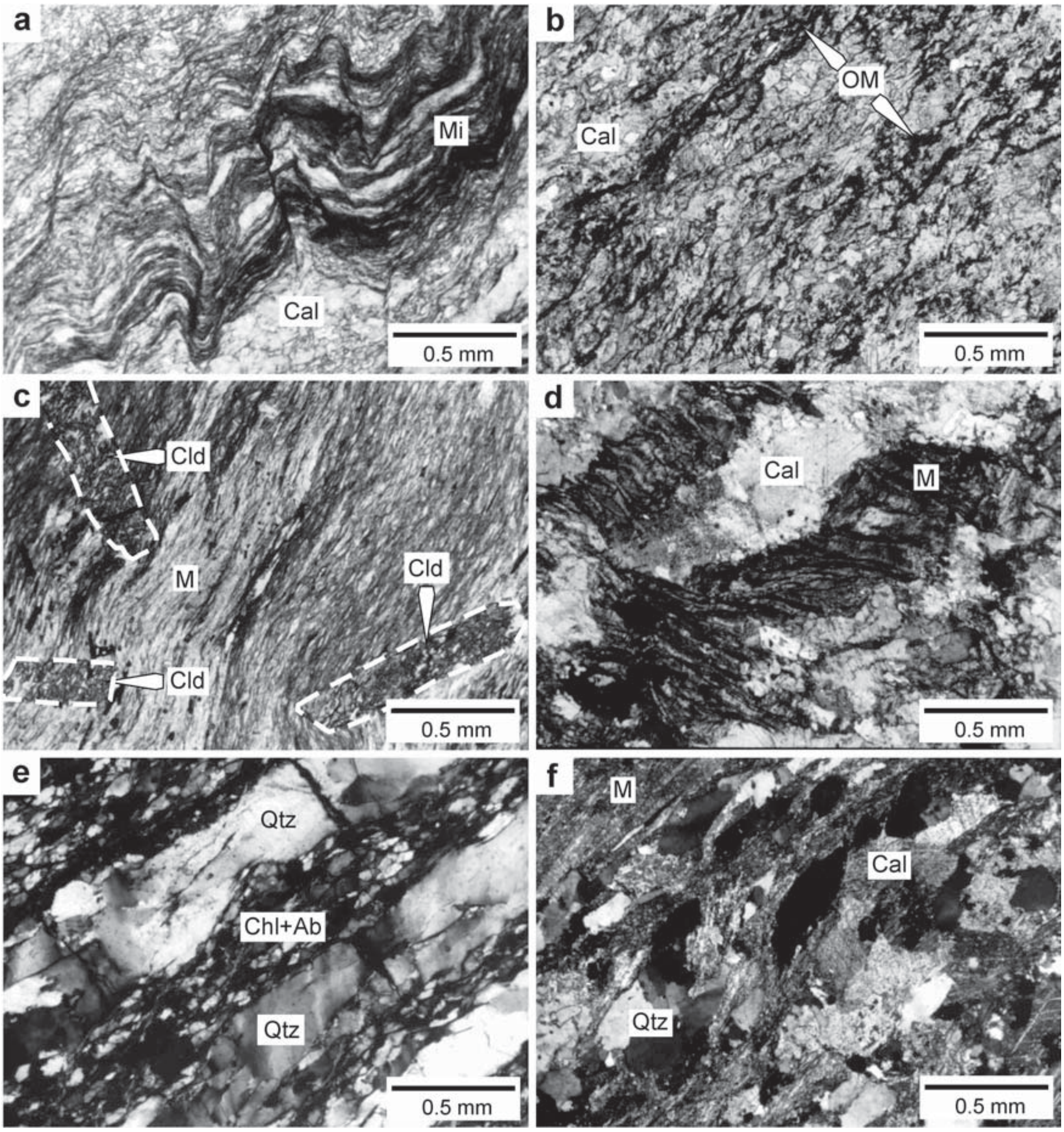

Fig. 3. Optical photomicrographs of textures and mineral assemblages in the SAMC (Cal = calcite, M = K-mica, OM = organic matter, Cld = chloritoid, Qtz = quartz, Chl = chlorite, on = open nicol, cn = crossed nicol). **a** — Crenulation cleavage in the calc-phyllites of Keban Metamorphics (KM-42, on), **b** — Thin organic matter layers orientated along the foliation planes in the crystallized limestones of Keban Metamorphics (KM-36, on), **c** — Post-kinematic chloritoid porphyroblasts cutting the orientations of fine-grained white mica and chlorite mass in the phyllites of Malatya Metamorphics (MM-50, on), **d** — Carbonate and crenulated phyllosilicate-rich level laminations in the impure laminated marbles of the Malatya Metamorphics (ZB-183, cn), **e** — Recrystallized quartz and fine-grained albite-chlorite layers in the chlorite-albite schist of Carboniferous-Permian parts of the Pütürge Metamorphics (MM-32, cn), **f** — Lepido-granoblastic texture in the calcschist of Carboniferous-Permian parts of the Pütürge Metamorphics (PM-89, cn).

phyllite, calc-phyllite, albite-quartz phyllite, albite-mica-chlorite phyllite, albite-muscovite phyllite) with grey-green metabasic (epidote-albite-actinolite-chlorite schist) rocks, grey-black metalimestone and scarce quartzite interbeds. The phyllites are characterized by typical crenulation cleavage. The metacarbonate levels locally include thin phyllite microlaminations and may be classified as metalimestone/marble with phyllite laminations. The metabasic levels have a typical mineral paragenesis of epidote + tremolite/actinolite + chlorite + albite ± biotite. In addition, organic-matter-rich levels — up to 2–3 m in thickness within the crystallized limestones and phyllites — are characteristic of the upper levels of the unit (Fig. 3b). Such occurrences have been noted within the Carboniferous-Permian sedimentary rocks of the Eastern Taurus Autochthon (Bozkaya & Yalçın 2004b).

The upper metacarbonate member (i.e. the uppermost unit of the Keban Metamorphics) consists of pink-white recrystallized limestone, scarce claret red and brownish recrystallized dolomites and metamarls. Dolomite levels (1 m) and thin-bedded metamarls are found in the middle to upper levels of the unit. The recrystallized limestones are characterized by microgranoblastic, partly stylolitic and brecciated textures. Primary sedimentary features, such as micrite-sparite microlaminations and fossils, are partially preserved in some of the recrystallized limestones. The recrystallized dolomites have finer-grained crystals relative to the recrystallized limestones.

Malatya Metamorphics

The Malatya Metamorphics were studied south of Yeşilyurt and east of Doğanşehir (Fig. 1b). This unit was divided into lower (schist, calc-schist) and upper (marble) metamorphic units. In this study, the Malatya Metamorphics were investigated as lower metapelites, slates partially laminated with marbles, upper metacarbonates, and marble partially laminated with slates (Yalçın et al. 1999).

The main lithologies of the lower metapelites, 750–1000 m thick, comprise greenish-brownish slates and yellowish-brown slates laminated with thin marbles and greenish metasandstones (Fig. 4). Chloritoid-bearing phyllites and metasandstones — characteristic lithologies along the thrusted boundaries of the Malatya Metamorphics — crop out east of Doğanşehir in the thrust zone between staurolite-bearing metapelites of the Pütürge Metamorphics and metacarbonates of the Malatya Metamorphics (Fig. 5). Chloritoid porphyroblasts are randomly oriented by cutting sericite and chlorite planes in the schistose matrix and, therefore, are of post-tectonic origin (Fig. 3c). Slates and especially phyllitic slates in the upper parts of this unit have well-developed crenulation cleavage (Kisch 1991; Guidotti et al. 2005), and also contain recrystallized quartz lenses in the matrix of the fine-grained phyllosilicates (sericite and chlorite). The calcite and extremely low dolomite contents of the slates increase up to 30 % upward, due to 0.5–2-mm-thick metacarbonate laminations. These rocks were termed slates with marble laminations, instead of calc-schist, in the definitions of some earlier workers (Karaman et al. 1993; Yılmaz et al. 1993). Metapelitic rocks are partially intercalated with metacarbonates (marble and dolomitic marbles) and metaclastites (metasandstones and metasiltstones). The albite and chlorite contents increase in the metaclastic rocks, and quartz and albite grains have sutured boundaries with fine-grained matrix.

The upper metacarbonates, ~700 m thick, comprise thick-bedded, partially brecciated greyish to black-brown marbles and dolomitic marbles (Fig. 4), including intercalations of slates, metasiltstones, metasandstones and scarce metavolcanites. These rocks typically have grano-

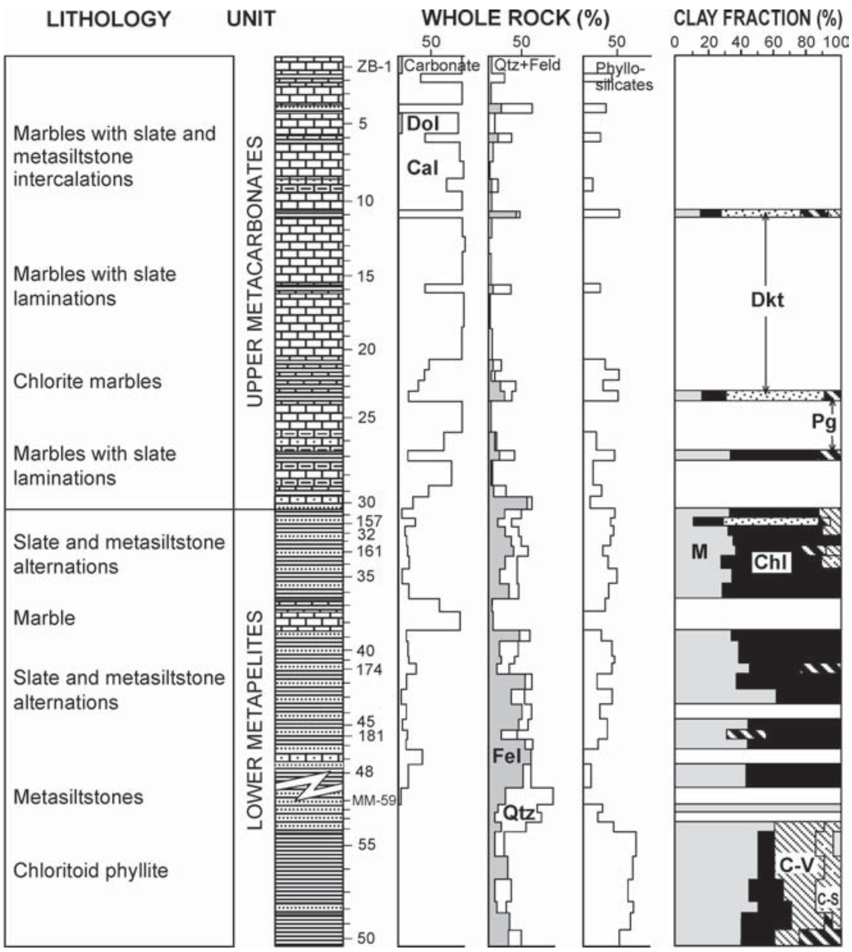

Fig. 4. Vertical distributions of the lithology and mineralogical composition of the Malatya Metamorphics (Dkt = dickite, Pg = paragonite, C-S = mixed-layered chlorite-smectite. Other mineral abbreviations as in Fig. 2).

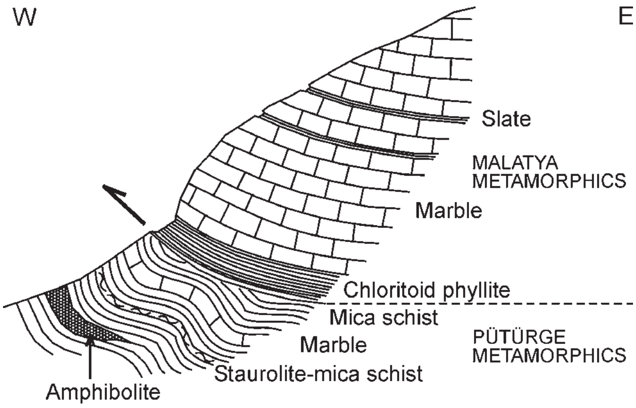

Fig. 5. Cross-section of overthrusting of Malatya Metamorphics with chloritoid-bearing zone on the Pütürge Metamorphics in the eastern Doğanşehir region.

blastic sutured textures, and contain crenulated slate laminations (0.5–2 mm thick) in some levels, giving a schist-like appearance (Fig. 3d). These rocks comprise marbles with slate laminations, reflecting a primary sedimentary feature (rather than the effects of metamorphic differentiation) because of the low-metamorphic grade. In addition, spherical and ellipsoidal oolites/pisolites (0.5–15 mm) with chlorite lamellae were noted in one slate sample. These allochems are characteristic of this unit; similar levels have also been reported in the lowermost parts of the Permian Aladağ Unit in the Aygörmez Dağ (Pınarbaşı-Kayseri) area (Bozkaya & Yalçın 2004b). Metavolcanic rocks with blastoporphyritic texture consist mainly of plagioclase and scarce quartz, with an entirely chloritic matrix.

Pütürge Metamorphics

These rocks were studied in the Pütürge and Doğanşehir areas, wherein outcrops of these lithologies are abundant. This unit constitutes the relative basement of the two areas, and comprises Precambrian-Devonian high-grade metamorphic rocks (augen gneisses, amphibolites, mica schist/gneisses, granitic gneisses) in its lower parts and Carboniferous-Permian low-grade metamorphic rocks (calc-schists/marbles and schists) in its uppermost parts. This cover unit, at least 500 m thick, is metamorphosed to greenschist facies and is similar to weakly metamorphosed marbles of the Bitlis Massif (Yazgan 1987).

Yellowish-white augen gneiss in the lowermost parts of this unit has thick foliation with cataclastic texture, and consists mainly of quartz, plagioclase (partly myrmekitic), orthoclase (partly perthitic), muscovite, biotite and chlorite, and has holocrystalline granular texture, reflecting its original granitic nature. Yellowish-brown, grey-black garnet-mica schists/gneisses from the middle to upper parts are better foliated and becoming lustrous, and some contain marble and amphibolite lenses. Schists and gneisses — the most widespread lithologies in the Pütürge area — can be listed (in ascending order) as kyanite-mica schists, biotite-amphibolites, garnet-kyanite-muscovite mica schists, garnet-andalusite-mica gneisses/schists and albite-chlorite-muscovite schists, and calc-schists. Sillimanite-mica, garnet-biotite, kyanite-biotite-albite and kyanite-staurolite-sillimanite gneisses/schists also occur in the Doğanşehir area. Amphibolite lenses from the lower and middle parts of the unit are composed of tschermakitic hornblende and plagioclase, and show typical grano-nematoblastic texture.

Brownish grey-black marbles (quartz-albite marble, chlorite marble), calc-schist alternations, and grey-brown chloritic and albitic schist intercalations (Fig. 6) occur in upper levels within both the Pütürge and Doğanşehir areas and constitute a low-grade (greenschist-facies) metamorphic cover for the high-grade metamorphic rocks. Recrystallized quartz layers alternate with fine-grained chloritic-albitic layers in some chlorite-albite schists

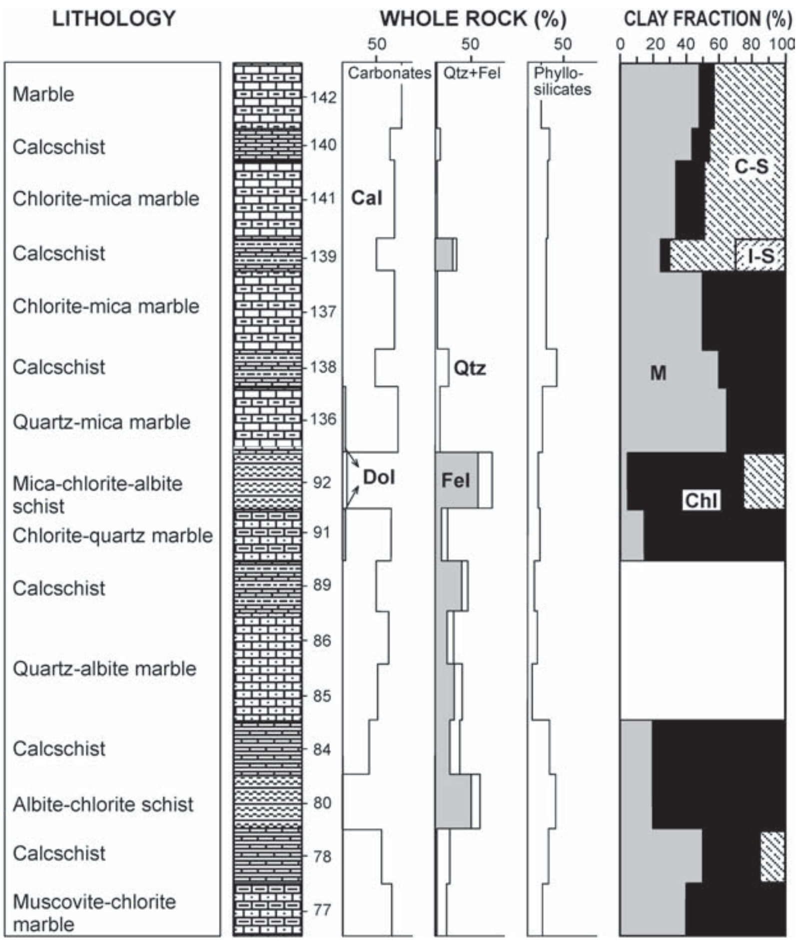

Fig. 6. Vertical distributions of the lithology and mineralogical composition of Carboniferous-Permian parts of the Pütürge Metamorphics (mineral abbreviations as in Fig. 2).

(Fig. 3e). The calc-schists are typified by lepido-granoblastic texture and contain oriented muscovite and biotite minerals within a calcitic groundmass (Fig. 3f).

X-ray mineralogy

Keban Metamorphics

The metamorphic rocks are composed, in order of abundance, mainly of calcite, phyllosilicates, quartz, albite and dolomite. Phyllosilicate minerals include illite, smectite, chlorite, kaolinite, and scarce mixed-layered chlorite-smectite (C-S), chlorite-vermiculite (C-V) and illite-smectite (I-S) (Fig. 2). The main phyllosilicate associations are illite + vermiculite + smectite, illite + kaolinite + smectite ± chlorite, smectite + illite ± C-S ± I-S ± kaolinite, chlorite + illite ± kaolinite ± smectite, illite + chlorite + kaolinite (Fig. 7). The presence of smectite and smectite-bearing mixed-layers in the epimetamorphic rocks seems to be related to metacarbonates and organic-material-rich rocks. As previously indicated by Frey (1987), in metacarbonates and organic-matter-rich sediments, smectites may persist into the epizone, and the aggradation of illite may be retarded (as compared to metaclastites) by a deficiency of potassium.

b_0 cell dimensions range from 0.8990 to 0.9035 nm and average 0.9014 nm for the muscovitic-phengitic white K-micas (Table 1), indicating the lower parts of the intermediate-pressure facies of Guidotti & Sassi (1976). $d_{060,33\bar{1}}$ values for white K-micas in the biotite-bearing samples reflect the totally phengitic composition. $d_{060,33\bar{1}}$ or b_0 values and basal peak ratios for the K-micas from the three rock units are plotted in Fig. 8. The biotite-bearing samples show lower basal peak ratios than the muscovitic ones, as previously suggested by Esquevin (1969).

Chlorites in the Keban Metamorphics are chamosite and clinochlore; their Si contents are higher than those of chlorites in the Malatya and Pütürge Metamorphics (Table 2; Fig. 9). Consistent with the conclusions of Zane et al. (1998), the large variations in the Fe and Mg contents of the chlorites are related to a wide variation in bulk-rock compositions; chlorites in the calcareous phyllites have relatively higher Fe than those in the metabasic rocks (Table 2).

KI values for the K-micas of 11 samples, lacking or containing only minor carbonate, indicate epizonal conditions (Fig. 10), except for two biotite-bearing samples with higher KI values. This anomaly reflects the broad interference effect of biotite basal peaks (Frey 1987). AI values for the chlorites also indicate epizonal conditions. The polytypes of the micas are $2M_1$ and $1M$ for muscovites

Table 1: Crystallochemical data of white K-micas and organic reflection values.

Unit	b_0 (nm)			KI (Δ°2θ)		AI (Δ°2θ)		Basal spacings (nm)		OMR (Rm_{oil} %)		
	n	Mean	S.D.	n	Range	n	Range	n	Range	n	Mean	S.D.
Keban	23	0.9014	0.001	11	0.19–0.31	5	0.17–0.29	–	–	56	6.22	0.59
Malatya	21	0.9005	0.001	39	0.12–0.29	24	0.09–0.24	9 9	0.9950–1.0030 (Mu) 0.9595–0.9635 (Pa)	20	5.84	0.61
Pütürge (LGM)	5	0.9026	0.001	7	0.19–0.25	–	–	–	–	–	–	–
Pütürge (HGM)	19	0.9005	0.001	–	–	–	–	–	–	40	8.07	0.95

nm — Nanometer, n — Number of samples, S.D. — Standard deviation, OMR — Organic matter reflection, LGM — Low grade metamorphic part, HGM — High grade metamorphic part.

Table 2: Mean basal reflections, peak intensity ratios and structural formulas of chlorites.

Unit	n	d_{001} (nm)	I[(002)+(004)]/ I[(001)+(003)]	I(002)/ I(001)	I(004)/ I(003)	Si^{IV}	Al^{VI}	Fe^{VI}	Mg^{VI}	Lithology
Keban	3	1.429	1.89	2.57	1.49	3.10	0.90	1.37	3.73	Ep-Ab-Act-Chl-schist
	18	1.422	2.62	3.10	2.23	2.87	1.13	2.50	2.37	Calcphyllite/Calcschist/Marble
	3	1.422	2.40	2.91	2.07	2.85	1.15	2.37	2.48	Phyllite
Malatya	7	1.417	3.35	4.19	2.60	2.69	1.31	3.33	1.36	Metasandstone/Metasiltstone
	24	1.419	2.97	3.94	2.20	2.67	1.33	2.91	1.76	Calcslate/Marble
	21	1.418	2.99	3.90	2.33	2.69	1.31	2.97	1.72	Slate
Pütürge (LGM)	7	1.415	2.13	2.52	1.86	2.60	1.40	1.81	2.79	Ms-Chl-Ab-schist
	5	1.417	1.95	2.75	1.61	2.70	1.30	1.64	3.06	Calcschist/Marble

nm — Nanometer, n — Number of samples, LGM — Low grade metamorphic part.

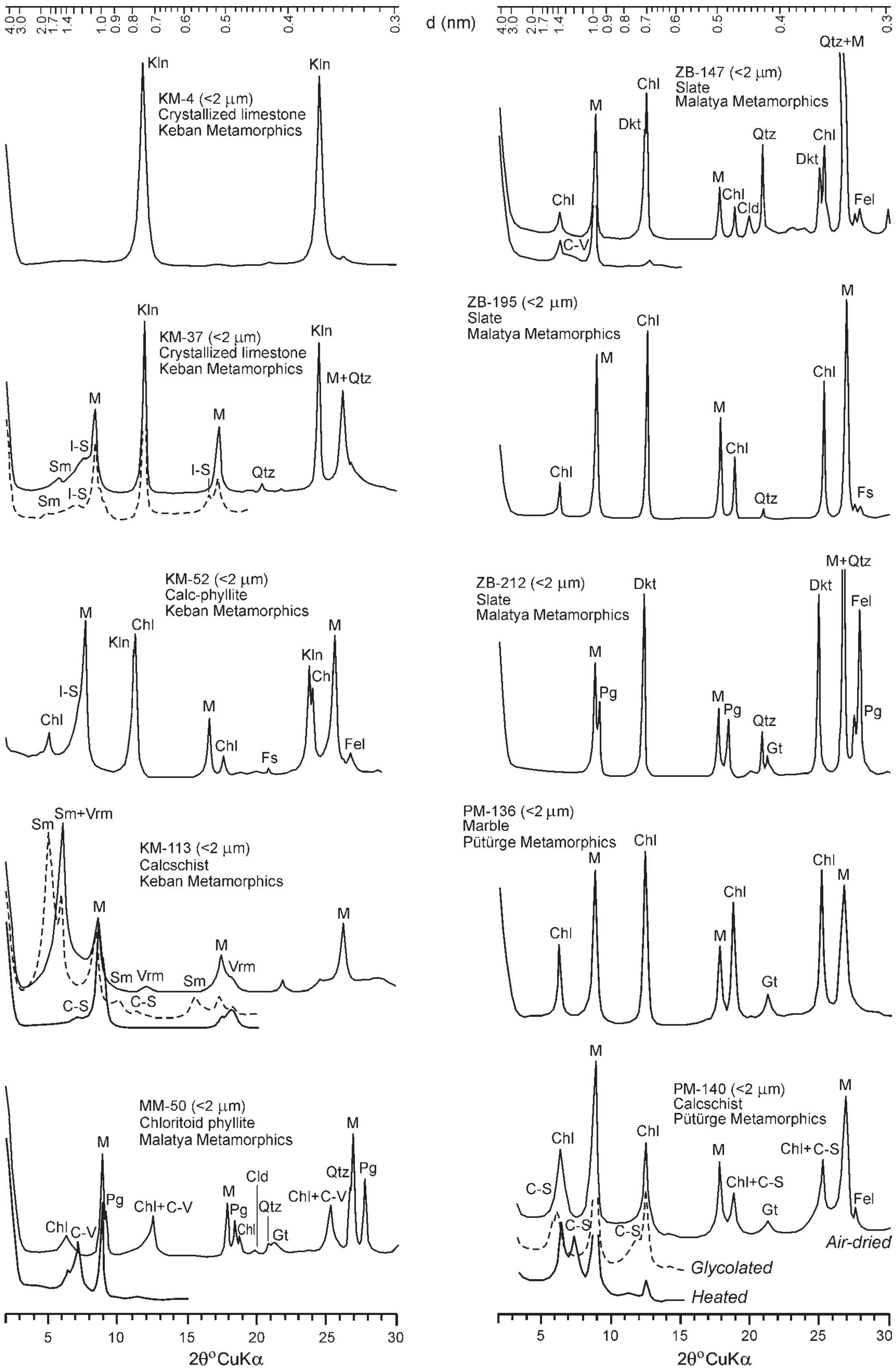

Fig. 7. Representative diffractograms of common phyllosilicate assemblages in the SAMC (Kln = kaolinite, M = K-mica, Chl = chlorite, Pg = paragonite, Dkt = dickite, Vrm = vermiculite, C-S = mixed layered chlorite-smectite, C-V = mixed layered chlorite-vermiculite, I-S = mixed-layered illite-smectite, Sm = smectite, Cld = chloritoid, Qtz = quartz, Ab = albite, Gt = goethite).

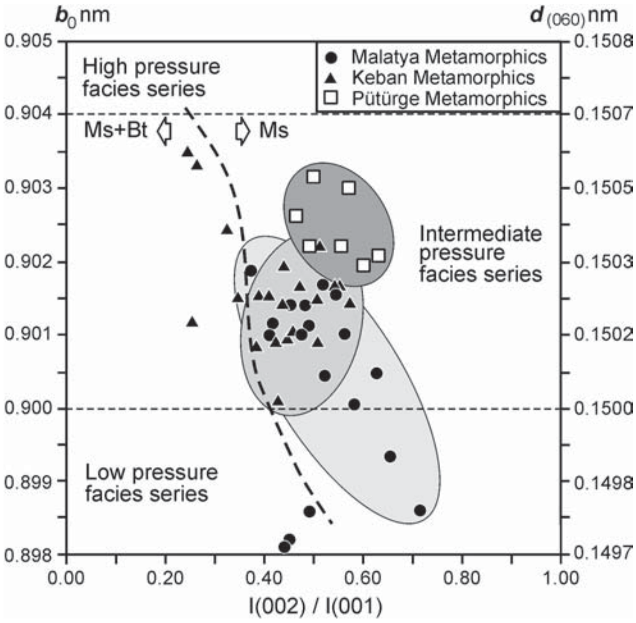

Fig. 8. d_{060} or b_0 cell dimension vs. I_{002}/I_{001} relationships in the K-micas. Pressure facies boundaries taken from Guidotti & Sassi (1986). S-shaped curve is indicated boundary between K-micas with biotite and without biotite (from Bozkaya & Yalçın 2004a).

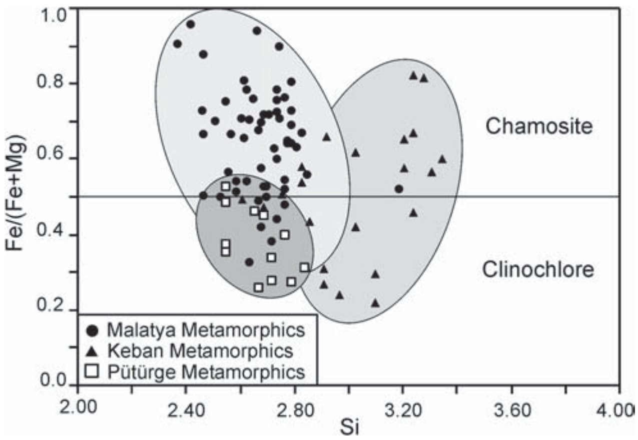

Fig. 9. Si-Fe/(Fe+Mg) contents of the chlorites (nomenclatures of clinochlore and chamosite from Bailey 1980).

and biotites, respectively. Chlorite and kaolinite-group minerals are of the *IIb* and kaolinite polytypes, respectively.

Malatya Metamorphics

The lithologies within this major unit are composed chiefly of phyllosilicates, quartz, albite, calcite, dolomite and chloritoid. Phyllosilicate minerals include muscovite, chlorite, paragonite, kaolinite/dickite, and minor C-V, C-S and I-S (Fig. 4). The most widespread phyllosilicate parageneses are muscovite+chlorite, muscovite + chlorite+paragonite, muscovite + chlorite + paragonite + kaolinite/dickite (Fig. 7). The appearances of mixed-layer C-V, C-S and smectite are inconsistent with the epizonal grade, and probably reflect retrograde alteration (e.g. Nieto et al. 1994) during post-metamorphic processes.

The paragonite components (i.e. interlayer cation Na) in muscovite, which coexists with paragonite, reach up to 20 % (mean 9 %); these values indicate temperature conditions lower than 400 °C according to the thermometric diagrams of several authors (Chatterjee & Flux 1986; Blencoe et al. 1994; Guidotti et al. 1994a,b). The $d_{(002)}$ nm basal spacings of the paragonite and muscovite peaks are (Table 2), except for in two samples, outside the ranges suggested by Zen & Albee (1964); this may be a result of celadonitic substitution in muscovite (Chatterjee 1971; Mposkoz & Perdikatzis 1981; Guidotti et al. 1994c) or due to fine-grained paragonitic mica in the matrix (Craig et al. 1982; Dimberline 1986; Milodowski & Zalasiewicz 1991; Li et al. 1994).

The b_0 values of the white K-micas (0.8981–0.9025 nm, mean 0.9005 nm) indicate lower pressure conditions than those of the Keban Metamorphics. The b_0 values and basal peak ratios of the K-micas fall in different areas in the Pütürge and Keban Metamorphics (Fig. 8).

The Fe^{2+} contents of chlorites are higher than in the Keban and Pütürge Metamorphics, which show a mean chamositic composition $(Si_{2.68}\ Al_{1.32})_4\ (Mg_{1.64}\ Al_{1.32}\ Fe^{2+}_{3.04})_6\ O_{10}\ (OH)_4$ (Table 2; Fig. 9). The most Fe-rich chlorites are found in the metasandstones, metasiltstones and metacarbonates.

KI values ($\Delta°2\theta$=0.12–0.29, mean 0.17) for 39 samples correspond to epizonal conditions (Fig. 10). AI values are within the range $\Delta°2\theta$=0.09–0.24 (mean 0.13) suggesting similar conditions (Árkai 1991). The muscovite and chlorite are of the *2M*$_1$ and *IIb* polytypes, respectively.

Pütürge Metamorphics

The Carboniferous-Permian low-grade metamorphic cover rocks of the Pütürge Metamorphics are probably equivalent to levels in the Keban and Malatya Metamorphics, and are made up mainly of calcite, albite, quartz and phyllosilicates.

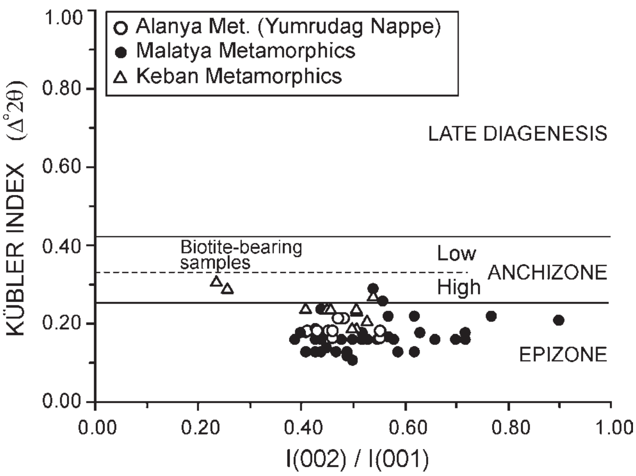

Fig. 10. Kübler index vs. I_{002}/I_{001} diagram in the K-micas (data related to Yumrudağ Nappe of Alanya Metamorphics from Bozkaya & Yalçın 2004a).

The clay fractions of these rocks comprise illite, chlorite, C-S and I-S (Fig. 6). The principal phyllosilicate assemblages are illite+chlorite, illite+C-S±chlorite and/or I-S (Fig. 7). The amounts of C-S and I-S increase upwards, especially in the calc-schists.

The b_0 values of the white K-micas range from 0.9019 to 0.9032 nm (mean 0.9026 nm), revealing a phengitic composition indicative of higher pressure conditions than the Keban and Malatya Metamorphics (Fig. 8).

Chlorites in the metacarbonate rocks have Mg-rich compositions — namely clinochlore; their chemistries plot in a small field which differs from the chlorites of the Malatya and especially the Keban Metamorphics (Fig. 9). With regard to phyllosilicate polytypes, the muscovite and chlorite are $2M_1$ and *IIb*, respectively.

Organic-matter reflectances

The reflectance measured in six metapelite samples from the Keban and Malatya Metamorphics varies from 5.33 to 7.32 Rm_{oil}% (mean 6.22 Rm_{oil}%) and 4.52 to 6.58 Rm_{oil}% (mean 5.84 Rm_{oil}%), respectively. The rank of coalification corresponds to the meta-anthracite to semi-graphite stages (Teichmüller 1987). High standard-deviation numbers for randomly measured OMR (organic matter reflection) values (Table 1) indicate high anisotropy (or bireflectance) for the organic matter.

Discussion and conclusions

The metamorphic units in the southeast Anatolian orogenic belt are characterized by distinct differences in regard to their textures and especially their mineralogical compositions; however, these units show rather similar stratigraphic and lithological characteristics.

The index metamorphic minerals of the metabasic levels of the Keban Metamorphics are represented by epidote, tremolite/actinolite, albite and biotite. The phyllosilicate minerals are characterized by kaolinite, smectite, vermiculite, I-S and Al-poor chlorites. An epidote + albite + tremolite/actinolite + *IIb* chlorite ± *1M* biotite assemblage, epizonal KI values, and moderate b_0 values in $2M_1$ white K-micas reflect the intermediate-pressure facies and organic-matter reflectance values show meta-anthracitic maturation, thus indicating metamorphism below ~300–400 °C temperature with pressures of ~0.5–0.6 GPa. Phengitic micas with moderate b_0 values, and mica and chloritic associations indicate low heat flow (< 25 °C/km) and moderate- to high-pressure conditions in a convergent basin (e.g. Merriman & Frey 1999; Merriman 2005). The tectonic microfabrics are typically parallel or subparallel to bedding planes, and rarely inclined and crenulated as a result of bedding-plane slip and imbrication, as noted by Merriman (2002) for fabric development in convergent basins.

The Malatya Metamorphics are represented by chloritoid, paragonite, dickite and Mg-rich chlorites. The index-mineral assemblages (chloritoid, paragonite, dickite), epizonal crystallinity, meta-anthracitic coalification degrees and lower b_0 values for the $2M_1$ white K-micas indicate a low-pressure facies, with ~300–350 °C and ~0.3–0.4 GPa temperature and pressure conditions, respectively. Phengite-poor micas with low b_0 cell dimensions and the presence of dickite and $2M_1$ paragonite show a metamorphic event that originated under relatively high heat-flow conditions (> 35 °C/km) in an extensional setting (e.g. Merriman & Frey 1999; Merriman 2005). The abundance of well-developed slaty and crenulation cleavages in the anchi-epimetamorphic rocks is assumed to reflect temperatures reached within an extensional-basin setting, which was maintained during basin inversion and deformation, thus enhancing ductile strain, recrystallization and cleavage development (e.g. Warr et al. 1991; Bozkaya & Yalçın 2004b). This evolution marks a counterclockwise P-T-t evolution in an extensional basin (Fig. 11).

Low- and high-grade metamorphic parts of the Pütürge Metamorphics are composed of index minerals such as epidote, albite, biotite and amphibole, garnet, staurolite, kyanite, sillimanite and andalusite minerals, respectively. The Carboniferous-Permian low-grade metamorphic parts comprise phyllosilicates such as epizonal $2M_1$ white K-mica, Mg-rich *IIb* chlorite, and C-S and reflect the metamorphism under ~300–400 °C temperature and pressures of ~0.5–0.6 GPa in a convergent basin.

The appearance of smectite and mixed-layer clay minerals (C-V, C-S and I-S) in high anchizonal to epizonal metamorphic rocks from the Keban, Malatya and Pütürge Metamorphics is inconsistent with the metamorphic index-mineral phases; thus, these may reflect lithological effects (Frey 1987) and post-metamorphic alteration processes (Nieto et al. 1994).

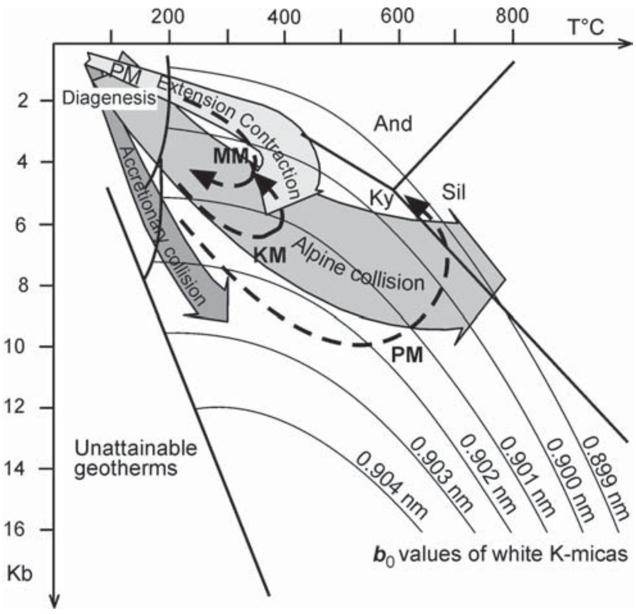

Fig. 11. Hypothetical metamorphic evolution of the SAMC showing the different metamorphism characteristics on the basis of their tectonic settings (b_0 lines from D'Amico et al. 1987; tectonic settings from Merriman & Frey 1999).

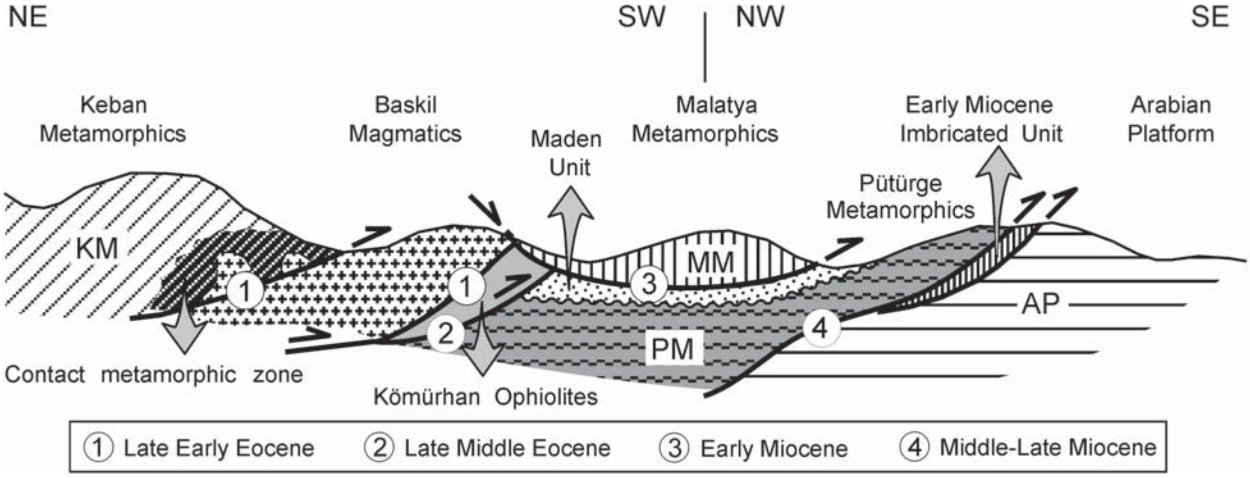

Fig. 12. Schematic section displaying the tectonic structure of the Southeast Anatolian Metamorphic area.

Data obtained from coeval parts of the Malatya and Keban Metamorphics demonstrate that these are of different origin; this contradicts the hypothesis that they shared a common origin (Yılmaz 1993). Thus, the compound classification — the "Keban-Malatya Unit" — of Yılmaz et al. (1993) is probably incorrect.

The Keban and Malatya Metamorphics are known to be of Tauride origin, as previously suggested by many authors (e.g. Yazgan 1984; Göncüoğlu & Turhan 1984; Yazgan & Chessex 1991; Yılmaz 1993; Yılmaz et al. 1993); but those workers did not explain the origin of the Tauride units. However, Yılmaz et al. (1993) suggested that the Keban Metamorphics originated from the autochthonous Geyikdağı Unit, as concluded in the present study. Coaly metacarbonate levels and phyllosilicate compositions suggest that the Keban Metamorphics were derived from the Eastern Tauride Autochthon or Geyikdağı Unit (Bozkaya & Yalçın 2004b), whereas the Malatya Metamorphics show important lithological (chloritic oolitic/pisolitic levels) and mineralogical (Na-mica, dickite and white K-micas with low b_0 values) similarities to the allochthonous Aladağ Unit.

The contrasting *P-T* evolutions of the SAMC are related to their being metamorphosed in different geotectonic settings. The Keban and Pütürge Metamorphics developed in an Alpine collision zone, whereas the Malatya Metamorphics developed in an extensional marginal basin, and clearly do not provide evidence of a collisional setting (Fig. 11). Therefore, the Malatya Metamorphics must be allochthonous; that is, transported from another source. Structural orientations indicate southward emplacement. In particular, mineralogical and lithological similarities with northern allochthonous Tauride units (Bolkardağı and Aladağ Units; Bozkaya & Yalçın 2004b) imply an origin from the north for the Malatya Metamorphics (Fig. 12). In the light of the thrusted boundaries with the Middle Eocene Maden Unit, and the unconformably overlying Early Miocene sedimentary rocks, the allochthonous transport of the Malatya Metamorphics must have occurred in the post-Eocene–Early Miocene time interval. This tectonic event corresponded to a second major episode of Alpine deformation in the southeast Anatolian orogenic belt.

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