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# Textural and mineralogical evidence for a Cadomian tectonothermal event in the eastern Mediterranean (Sandıklı-Afyon area, western Taurides, Turkey)

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**Abstract**

In the Sandıklı-Afyon area, the very low-grade metamorphic Sandıklı Basement Complex with clastic sediments and Late Neoproterozoic felsic igneous rocks are unconformably overlain by a cover succession with red continental clastic rocks, tholeiitic basalts and siliciclastic rocks with Early Cambrian trace fossils. Illite crystallinity studies reveal that both the basement and cover units were metamorphosed at high anchizonal to epizonal conditions (~300 °C). Textural data together with the detailed evaluation of the $P$–$T$–$b_0$ grid, however, indicate that this thermal event has multiple phases. The first tectonothermal event was realized at pressures of ~4.2 kb on the basis of $b_0$-data and resulted in development of blastomylonites. This is supported by the presence of dynamo-metamorphosed pebbles within the basal conglomerates of the Lower Paleozoic cover series. The second event is post-Ordovician–pre-Jurassic in age, occurred at lower pressures ~3.2 kb and produced a weakly developed cleavage in the siliciclastic rocks of the cover. The mineralogical/textural data across the basement-cover boundary therefore indicate the removal of an entire metamorphic zone and thus a metamorphic hiatus.

These data suggest that the Taurides were affected by a Late Neoproterozoic event as part of the peri-Gondwana during the Cadomian orogeny.


*Keywords:* Cadomian; Very low-grade metamorphism; Mineralogy; Peri-Gondwana; Turkey

## 1. Introduction

The Cadomian orogeny was initially defined as a Late Neoproterozoic event in northern France that resulted in deformation and low-grade metamorphism of sedimentary rocks (Brioverian series) predating the deposition of Lower Cambrian continental clastics (Bertrand, 1921). Detailed studies (e.g., Murphy and Nance, 1989; Haydoutov, 1989; D'Lemos et al., 1990; Neubauer, 2002) have shown that this tectonothermal event was observed from the southeastern United States to central Europe and was accompanied by extensive magmatism.

Further east in the eastern Mediterranean, especially in the Taurides in southern Turkey and Iran, where Alpine orogeny has obliterated the traces of earlier events, Late Neoproterozoic and Early Cambrian sedimentary successions were included in the "Infracambrian Series" (e.g., Ketin, 1966). They were considered as continuous successions with local depositional breaks (e.g., Kozlu and Göncüoglu, 1997; Göncüoglu and Kozlu, 2000). Within the metamorphic massifs (e.g., Menderes, Kırsehir and Bitlis massifs; Fig. 1), on the other hand, the limited radiometric age data around 500 Ma were considered as indications of late Pan-African events (e.g., Göncüoglu et al., 1997; Loos and Reischmann, 1999; Candan et al., 2001). However, both for the Menderes Massif and the Taurides, the presence of a regional unconformity between the basement and the cover has been disputed (e.g., Erdogan et al., 2004). Moreover, the general consensus (Dean and Özgül, 1994; Göncüoglu and Kozlu, 2000; Gürsu et al., 2004; Gürsu and Göncüoglu, in press) for the paleogeographic position of the Taurides was that it remained in a platform-setting at the northern edge of Africa throughout the Paleozoic and Mesozoic and was only affected by the Alpine orogeny during the closure of the Neotethyan seaways (Özgül et al., 1991).

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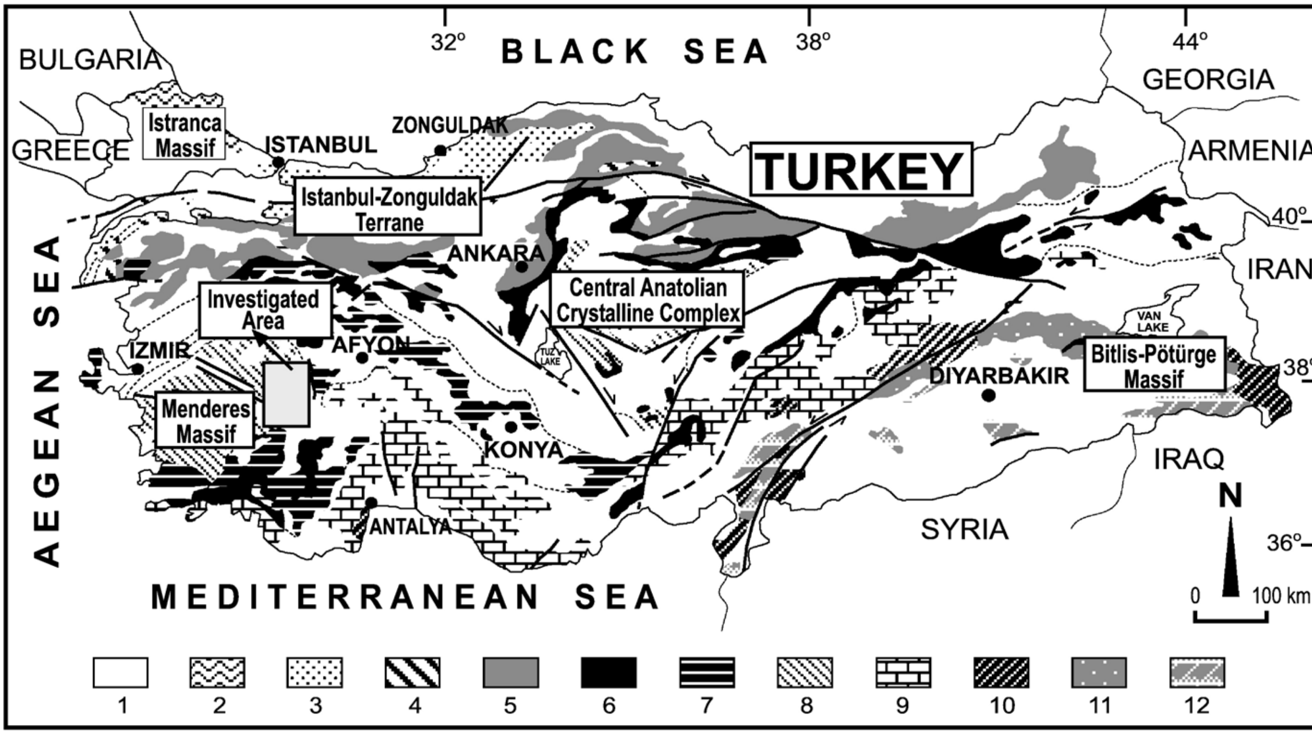


Fig. 1. Major Alpine units with Late Neoproterozoic–Early Paleozoic rock-units of Turkey and the locality of the study area. 1: Cenozoic cover, 2: Istranca Terrane, 3: Istanbul–Zonguldak Terrane, 4: Intrapontide Ophiolite Belt, 5: Sakarya Composite Terrane, 6: Izmir–Ankara–Erzincan Ophiolite Belt, 7–9: Taurides–Anatolide Terrane, 7: Kütahya–Bolkardag Belt, 8: Menderes Massif and Central Crystalline Complex, 9: Taurides, 10: Southeast Anatolian Ophiolite Belt, 11–12: Southeast Anatolian Zone, 11: Bitlis–Pötürge Massif, 12: Southeast Anatolian Autocthonous Belt (after Göncüoglu et al., 1997).

Recent work, however, has shown that both interpretations should be revised:

(a) Gürsu and Göncüoglu (2001) have shown that in western Central Taurides to the South of Afyon (Fig. 1), Early Cambrian rocks with Tommotian trace fossils (Erdogan et al., 2004) are found with a distinct angular unconformity above a slightly deformed and metamorphosed basement named as Sandıklı Basement Complex (Gürsu and Göncüoglu, 2001).
(b) Field data (Göncüoglu et al., 2001) indicate the presence of Variscan-aged unconformities along the northern margin of the Taurides.
(c) In the eastern Taurides, Bozkaya et al. (2002) pointed out that the sudden change of illite crystallinity and $b_0$ values of illite/white K-micas at the Neoproterozoic basement–Lower Paleozoic boundary may help to identify preserved fingerprints of a regional geological event.

To find out if a distinct Cadomian tectonothermal event occurred in the western Central Taurides, we applied detailed mineralogical studies to three different pre-Lower Cambrian to Lower Mesozoic successions. The authors selected the Afyon-Sandıklı area, which provides an opportunity to study the Late Neoproterozoic and Early Paleozoic evolution of the peri-Gondwanan Tauride Belt, because of the extremely weak Alpine deformation.

We considered several mineralogical indicators such as mineral assemblages, textures, illite crystallinity, illite/K-white mica $b_0$ cell dimensions, phyllosilicate polytypes etc. that have been used frequently for a better understanding of diagenetic to very low-grade meta-clastic rocks (e.g., Frey et al., 1980; Merriman and Roberts, 1985; Bevins and Robinson, 1988; Hesse and Dalton, 1991; Roberts et al., 1991; Yang and Hesse, 1991; Warr et al., 1991; Rahn et al., 1995; Offler et al., 1998; Merriman and Frey, 1999; Brime et al., 2001).

The aim of the present study is to establish pressure and temperature ($P$–$T$) conditions of Late Neoproterozoic, Lower Paleozoic and Jurassic rock-units and to interpret the geological history of the study area by means of the diagenetic–metamorphic data.

## 2. Geological setting and stratigraphy

The Tauride Belt in Turkey (Fig. 1) forms an E–W trending Alpine unit with numerous nappes and/or thrust sheets, formed during the closure of the Neotethyan oceans. It is widely accepted that it was located on northern marginal platform of Gondwana until the Early Mesozoic opening of the Southern Neotethyan oceanic seaway (e.g., Şengör and Yilmaz, 1981).

The Tauride Belt includes a variably metamorphosed basement both in the eastern and western Taurides (Öngür, 1973; Kröner and Şengör, 1990; Özgül et al., 1991; Dean and Özgül, 1994; Kozlu and Göncüoglu, 1997; Göncüoglu and Kozlu, 2000; Gürsu and Göncüoglu, 2001; Gürsu, 2002; Gürsu et al., 2004). More or less complete Neoproterozoic–Lower Paleozoic rocks in the Taurides are best exposed in the Geyikdag unit of Özgül (1976).

In the western central part of the Taurus Belt, around Sandıklı (Fig. 2), where the westernmost slightly metamorphic successions of the Geyikdag unit outcrop, the basement rocks are known as the Sandıklı Basement Complex (SBC; Gürsu, 2002). From bottom to top (Fig. 3), the SBC is composed of the Güvercinoluk Formation and the Kestel Cayi Porphyroid Suite (Gürsu and Göncüoglu, 2001). The Güvercinoluk Formation is characterized by an 800 m thick sequence of meta-sediments, consisting mainly of sandstones and shales, characterized by the presence of black chert (phtanite) bands and layers and associated carbonates, comparable to those in Iberia and Brittany (e.g., Vidal et al., 1994). The meta-magmatic rocks of SBC are named as Kestel Cayi Porphyroid Suite (KCPS, Gürsu and Göncüoglu, 2001) which is mainly composed of meta-rhyolites, meta-quartz porphyry rocks and meta-lamprophyre dykes. The meta-rhyolites of KCPS form dome-shaped bodies and have sheared intrusive contacts towards the Güvercinoluk Formation. The youngest zircon $^{207}Pb/^{206}Pb$ ages from the felsic intrusive rocks (543 ± 7 Ma; Kröner and Şengör, 1990; 541.3 ± 10.9 Ma; Gürsu and Göncüoglu, in press)

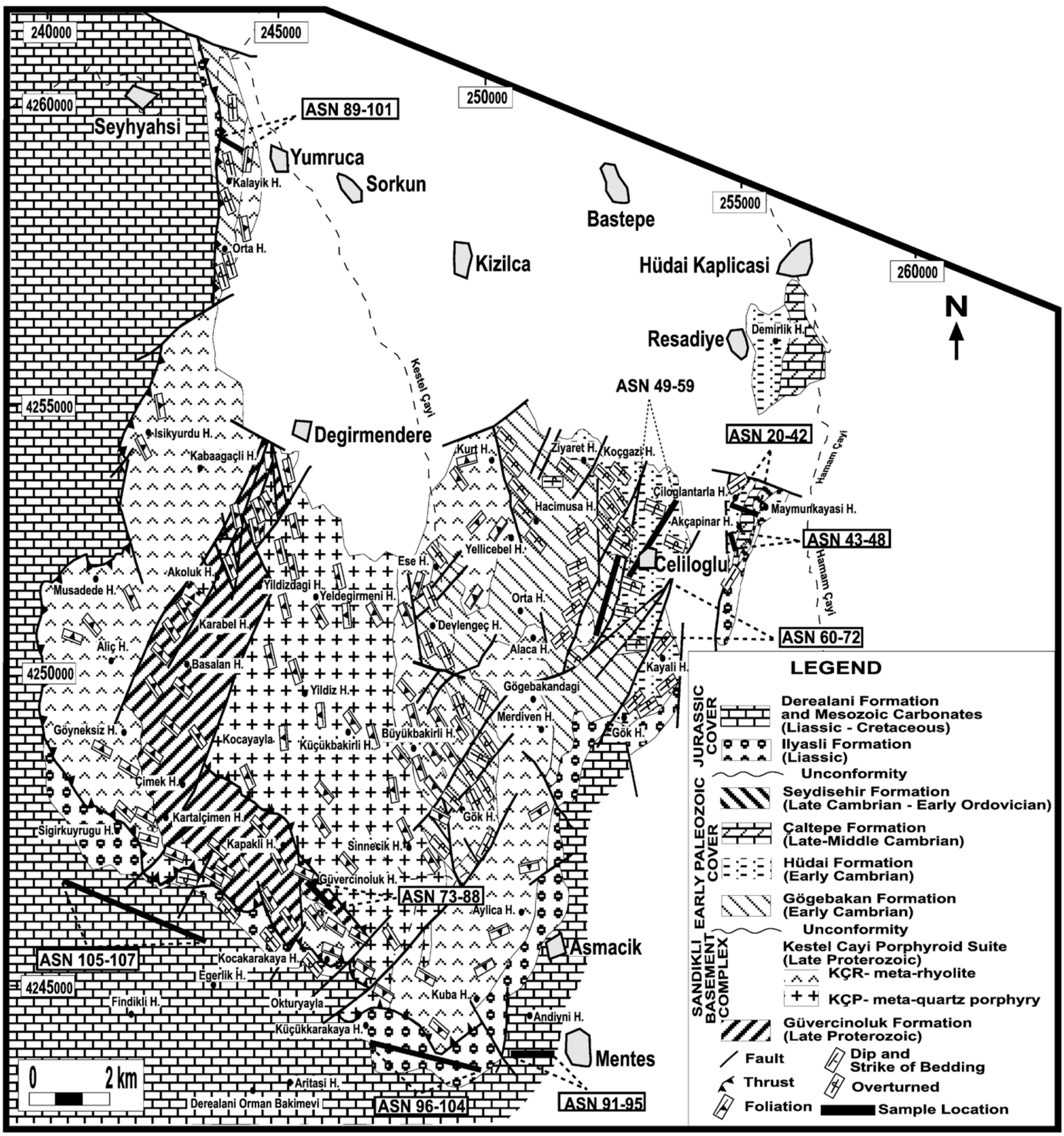


Fig. 2. Geological map of the studied area (after Gürsu, 2002) and locations of samples used for mineralogical studies.

suggest a Late Neoproterozoic age for the coeval volcanism (Gürsu et al., 2004). Geochemically, the complex represents the dominant felsic part of a bimodal magmatic suite, characterized by features of post-collisional/post-orogenic I-type granitoids (Gürsu et al., 2004).

The SBC is unconformably overlain by the Gögebakan Formation that consists of basal conglomerates that contain pebbles of meta-rhyolite, phtanite, phyllite and recrystallized limestone, all derived from the underlying rock-units, overlain by an alternation of intensively folded siliciclastic rocks with spilitic lava flows, pyroclastic rocks and meta-diabase dykes (Gürsu and Göncüoglu, 2005). The upper contact of this formation is transitional to the overlying Celiloglu member of Hüdai Formation and includes alternating quartzite and meta-

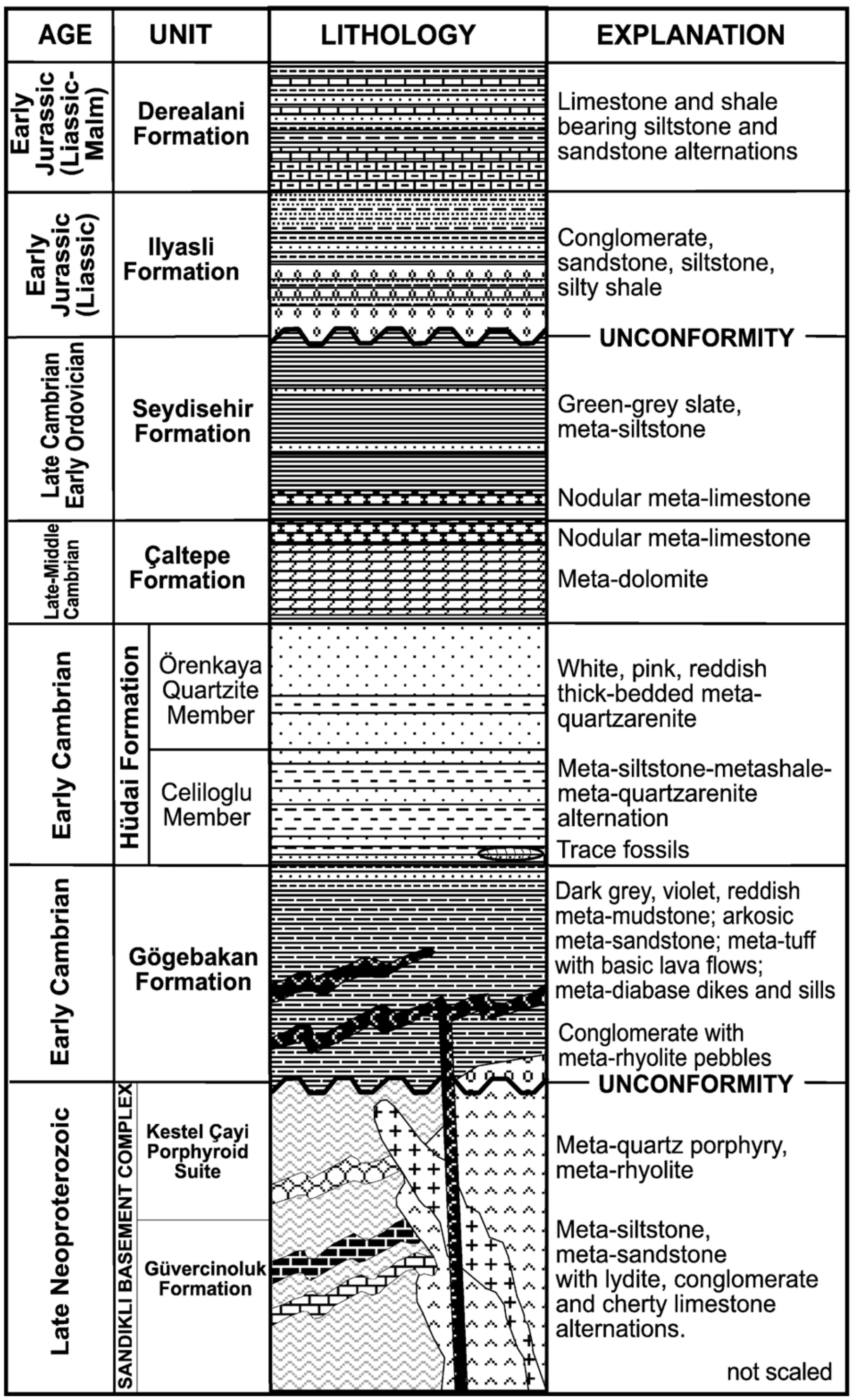


Fig. 3. Generalized lithostratigraphic section of the Sandıklı area (after Gürsu, 2002).

siltstone. In the transitional layers, trace fossils (*Cruziana*? *fasciculata*, *C.*? *salamonis*, *Rusophycus*? *avalonensis*, *R.*? *latus*, etc.) of Tommotian age have been reported by Erdogan et al. (2004).

The Celiloglu member is overlain by the Örenkaya Quartzite member, which is made up of laminated quartzite and meta-siltstone (Gürsu, 2002). The Hüdai Formation is succeeded by the Çaltepe Formation which predominantly consists of thick bedded, coarse dolomites, mostly pink, grey limestone and pink nodular limestone. In the study area, the uppermost member of this formation has yielded Middle Cambrian fossils (e.g., Dean and Özgül, 1994). The grey limestone at the lowermost part of the formation at its type locality in Seydisehir has yielded small shelly fossils that mark the Lower–Middle Cambrian transition (Sarmiento et al., 1997). The Middle Cambrian–Early Ordovician Seydisehir Formation conformably overlies the Çaltepe Formation and consists of storm-type (tempestide) deposits of interbedded sandstone–siltstone with pink nodular limestones at the base. The Seydisehir Formation is unconformably overlain by non-metamorphic Liassic Ilyasli Formation (conglomerate, sandstone, siltstone and silty shale) and Derealani Formation (siltstone and sandstone intercalated with limestone and shale) of Liassic–Malm age in the investigated area.

## 3. Material and methods

A total of 154 rock samples were collected along three measured sections in the basement, Lower Paleozoic and Lower Mesozoic rock-units. The samples were analyzed by optical and X-ray diffraction (XRD) methods.

Optical microscopy was used for the fabric analyses, and XRD investigations were applied for the qualitative mineralogy, paragenesis of whole rock and clay-fractions, illite crystallinity, illite and chlorite polytypes and illite/muscovite $b_0$ cell dimensions in clay fractions.

The XRD analyses were performed in a Rigaku DMAX IIIC diffractometer with the following settings: CuKα, 35 kV, 15 mA, slits (divergence = 1°, scatter = 1°, receiving-monochromator = 0.30 mm), scan speed 2°2$\theta$/min. Scan speed or rates are given 1°2$\theta$/min for oriented clay diffractograms and illite crystallinity measurements as recommended by Kisch (1991). Sample preparation and clay separation processes were performed at the Department of Geological Engineering, Cumhuriyet University (CU), Sivas-TURKEY. The semi-quantitative percentages of the rock forming minerals and clay-size fractions were calculated by the external standard method of Brindley (1980). Clay fractions (<2 μm) from the fine-grained meta-sedimentary rocks separated by the sedimentation method were analyzed under normal (air dried at 25 °C for 16 h), ethylene glycolated—EG (remained in a desiccator at 60 °C for 16 h) and heated (heating at 490 °C for 4 h) conditions. The different mixed-layer mineral phases were identified using the methods of Moore and Reynolds (1997).

The widths of the 10 Å illite peaks at half-height (Kübler Index: KI, Δ°2$\theta$) were measured by using the Kübler (1968) method. Five polished-slate standards and one mounted muscovite flake of Kisch (1980) and

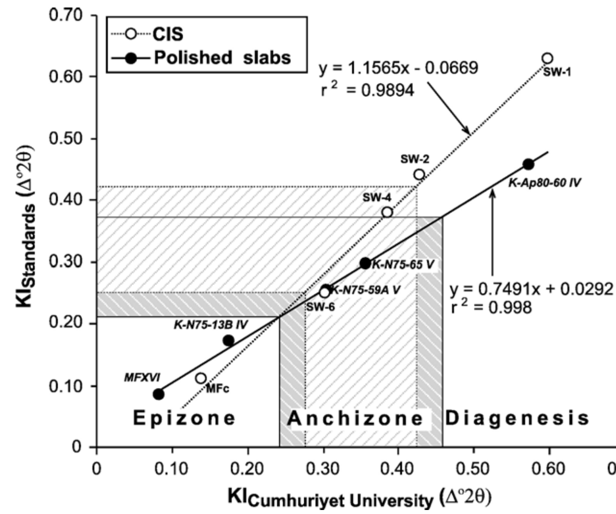


Fig. 4. Correlation of calibration lines using standard slabs of Kisch (1980) and CIS (Warr and Rice, 1994).

Crystallinity Index Standards (CIS) of Warr and Rice (1994) were used in calibration for KI measurements, and the linear-regression equations are $KI_{\text{Polished-slate standards}} = 0.7491 \times KI_{\text{Cumhuriyet University}} + 0.0292$ at $r^2 = 0.9980$ and $KI_{CIS} = 1.1565 \times KI_{\text{Cumhuriyet University}} - 0.0669$ at $r^2 = 0.9894$ (Fig. 4). All KI values are indicated and plotted as recalculated values. The upper- and lower-limits of the anchizone correspond to 0.21° and 0.37° Δ2$\theta$ for calibration with polished-slate standards (Kisch, 1980, 1990) and 0.25° and 0.42° Δ2$\theta$ for calibration with CIS (Warr and Rice (1994).

$d_{(060,\ 331)}$ reflections or $b_0$ cell dimensions were measured by means of the (211) peak of quartz (2$\theta$ = 59.982°, $d$ = 1.541 Å) as an internal standard. Octahedral Mg + Fe contents of illites/muscovites were determined on the basis of the regression equation of Hunziker et al. (1986).

Illite and chlorite polytypes were determined with the diagnostic peaks suggested by Bailey (1988) on non-oriented powder samples. To determine the $2M_1$ and $1M$ wt.% of $2M_1 + 1M_d$ or $2M_1 + 1M + 1M_d$ polytype-bearing illite/muscovites, the ratios of $I_{(2.80\ Å)}/I_{(2.58\ Å)}$ and $I_{(3.07\ Å)}/I_{(2.58\ Å)}$ were used, as proposed by Grathoff and Moore (1996).

## 4. Petrography

### 4.1. Güvercinoluk Formation

From bottom to the top, the meta-sedimentary rocks of the Güvercinoluk Formation are mainly represented by meta-siltstone with black colored phtanite and recrystallized dolomite lenses, grey-green colored turbiditic meta-sandstones, phyllite, phyllitic slate, recrystallized limestone and grey-light brown, cherty, laminated dolomitic limestone. The upper part of the formation consists of debris flow meta-conglomerates, grey-green meta-siltstone and phyllite. The phtanites are mainly composed of very fine-grained (10–15 μm) quartz and sericite. The phyllitic slates include chlorite, sericite, leucoxene, biotite, zircon and opaque minerals. The meta-sandstones comprise abundant deformed clasts of angular to sub-angular quartz, plagioclase and alkali feldspar embedded in a sericitic matrix with subordinate chlorite, graphite, leucoxene, tourmaline, zircon and opaque minerals. Recrystallized limestones are composed of calcite, quartz, sericite and chlorite. The meta-conglomerate in the upper part of the formation includes sub-rounded to angular fragments of phtanite, sandstone and limestone in a chloritic–sericitic matrix. The meta-siltstones and phyllites in the upper part of the succession are composed of angular–sub-angular clasts of quartz, plagioclase, alkali feldspar, chlorite, epidote, tourmaline, zircon and opaque minerals in a sericitic matrix and quartz + sericite + chlorite + graphite mineral paragenesis are observed indicating very low-grade metamorphism. Fine-grained recrystallized biotite in the matrix is typically present in the phyllitic slates and phyllites and meta-sandstones. The meta-pelitic layers show a well-developed N35°-trending schistosity, present discrete crenulation cleavage and commonly include macro and micro folds. Within the meta-pelitic rocks, discrete crenulation cleavage is well-developed ($S_1$). It is overprinted by an $S_2$ cleavage nearly 75° to $S_1$ and is accentuated by the parallel alignment of fine-grained sericite and chlorite flakes (Fig. 5a). In this case the separation into phyllosilicate-rich and quartz-rich domains is clearly seen. $S_3$ is only locally developed around the Alpine structures. It has overprinted and folded the $S_2$ fabric diagonally with low angles about 15° (Fig. 5a).

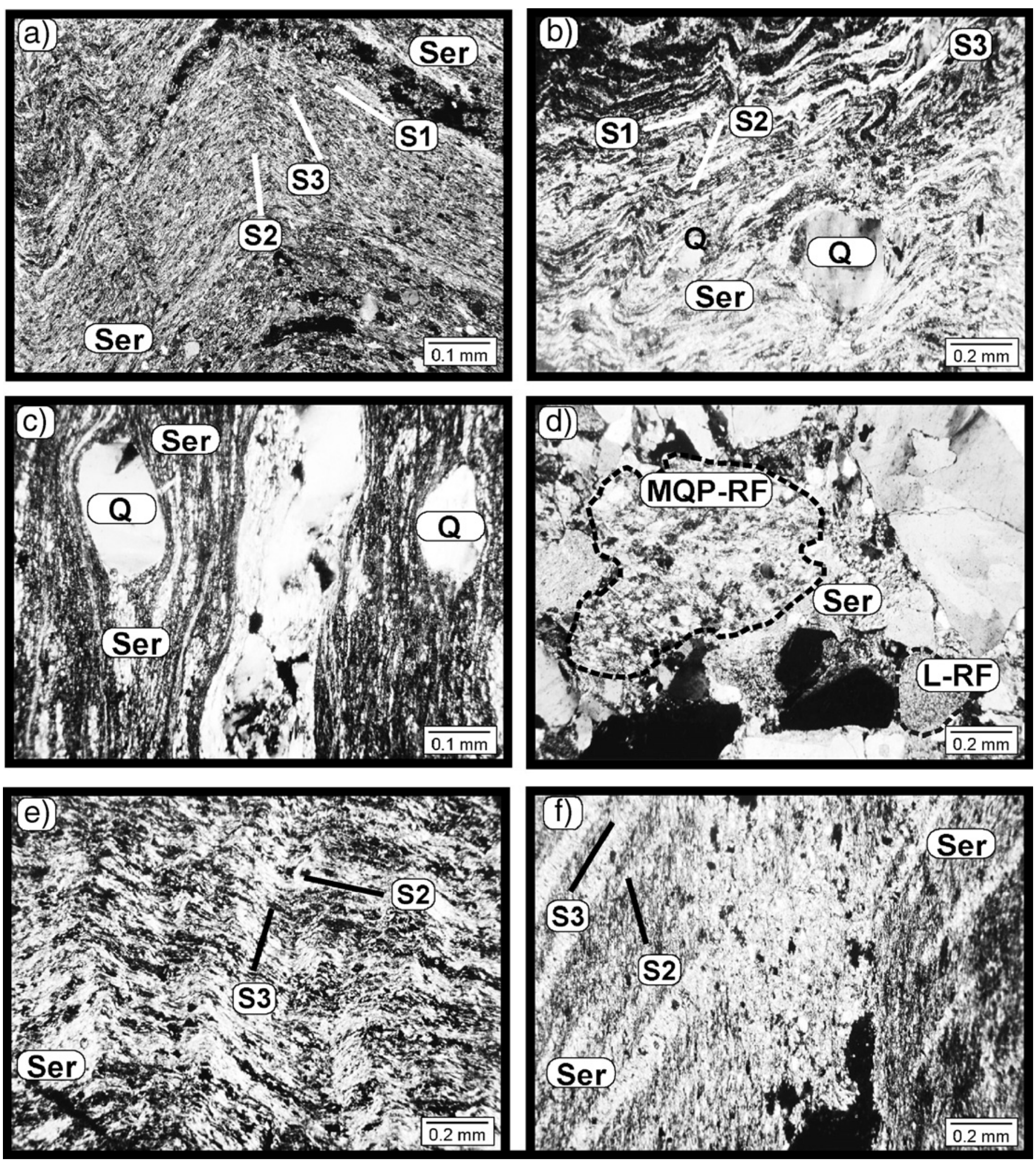


Fig. 5. Characteristic textural features of the Late Neoproterozoic basement and Early Paleozoic cover units in the Sandıklı area. a) well-developed S-planes in the meta-siltstones of Güvercinoluk Formation displaying three distinct deformational phases, b) crenulation folds and cleavages ($S_1$, $S_2$ and $S_3$) reflecting three distinct deformational phases in the meta-rhyolites of KCPS and σ-type quartz porphyroclasts, c) σ-type corroded quartz porphyroclasts (Q) embedded within a fine grained matrix in the mylonitic parts of the meta-rhyolites, d) basement-derived angular to sub-angular meta-quartz porphyry (MQP-RF) and lydite (L-RF) pebbles surrounded by a sericitic (Ser) matrix within the basal conglomerates of the Gögebakan Formation, e) crenulation folds and discrete cleavages ($S_2$–$S_3$) indicating two deformational phases in the slates/meta-mudstones of Gögebakan Formation, f) discrete cleavages ($S_2$–$S_3$) developed in meta-siltstones of Hüdai Formation.

### 4.2. Kestel Cayi Porphyroid Suite (KCPS)

KCPS is characterized by highly deformed meta-rhyolites and meta-quartz porphyry rocks that are cut by meta-basic dykes (Gürsu and Göncüoglu, 2001; Gürsu et al., 2004). The meta-rhyolites consist of euhedral to subhedral, corroded quartz and sanidine phenocrysts. The groundmass is replaced by neo-formed/recrystallized quartz, albite and coarse-grained sericite as a product of extensive mylonitic deformation and very low-grade metamorphism. Accessory minerals are epidote, zircon and opaque minerals (Fig. 5b). The meta-quartz porphyry rocks mainly include euhedral quartz porphyroclasts with typical skeletal structure, euhedral–subhedral microperthitic orthoclase porphyroclasts displaying micrographic texture and microcline porphyroclasts as variably deformed igneous phases. They are marginally recrystallized and surrounded by a mylonitized matrix with well-oriented and fine-grained recrystallized quartz and neo-formations of sericite with minor amounts of biotite, sphene, allanite, apatite, zircon and opaque minerals (Gürsu, 2002). In the mylonitic parts, they are elongated and show mortar texture (Fig. 5c). Similar to those in the Güvercinoluk Formation three distinct deformational phases (Fig. 5b) represented by variably penetrative foliation planes are observed. The finer-spaced penetrative one ($S_1$) parallels the main regional NNE−SSW foliation trend. $S_2$ deforms the $S_1$ fabric by a low-angle and is parallel to the foliation planes of the overlying Lower Paleozoic rocks. $S_3$ is restricted (Fig. 5b) to a narrow zone along the Alpine thrust-plane (see geological map on Fig. 2) along which the SBC overthrusts the Mesozoic cover units (Fig. 5b).

### 4.3. Gögebakan Formation

The Gögebakan Formation includes slightly metamorphosed conglomerate, sandstone and siltstone/mudstones alternating with pyroclastic rocks, spilitic lava flows and is cut by diabase dykes. The meta-pelites partly preserve a primary clastic texture compared to meta-pelitic rocks of the SBC. The apron type basal conglomerate mostly includes deformed, angular to sub-angular pebbles of the underlying meta-rhyolites and meta-quartz porphyry rocks with phtanite clasts in a sericitic matrix (Fig. 5d). Blasto-psammitic sandstones comprise sub-angular/angular clasts of quartz with undulating extinction, alkali feldspar, plagioclase and rock fragments (mainly deformed porphyroids and phtanite) of SBC, embedded in a sericitic matrix. Accessory minerals are tourmaline, chlorite, leucoxene, zircon and opaque minerals. The metamorphic mineral paragenesis of the meta-pelitic rocks of the formation is quartz + sericite + chlorite + calcite indicating low-grade metamorphism. Rarely, rounded chlorite-rich stacks indicate stretching of clastic volcanic micas during extension (Bozkaya and Yalcin, 2004) were detected in some meta-pelites. The spilitic meta-lavas commonly display amygdaloidal texture and comprise phenocrysts of albitised plagioclase and pyroxene as relict igneous phases. Authigenic chlorites were developed in the amygdales. The meta-spilites contain albite + calcite + sericite + epidote + tremolite + chlorite paragenesis indicating low-grade metamorphism. The meta-diabase dykes with blasto-ophitic texture mainly consist of plagioclase and pyroxene as primary phases and a matrix dominated by the metamorphic assemblage tremolite + epidote + chlorite. The fine grained clastic rocks of the formation are characterized by well-developed discrete crenulation-type cleavage. The earliest fabric is parallel to the $S_2$ of the underlying Güvercinoluk unit and is characterized by fine-grained sericite neo-formations (Fig. 5e).

### 4.4. Hüdai Formation

The lower member (Celiloglu) of the formation consists of interbedded quartz-arenites and siltstones. The quartz-arenite is predominantly composed of strained quartz, sericite and rare rock fragments (mainly deformed meta-felsic and meta-clastic rocks of SBC) within a sericitic matrix. The slightly metamorphic clastic rocks display also two sets of planar fabrics with oriented quartz and feldspar in a very fine-grained sericitic matrix (Fig. 5f). The overlying Örenkaya Quartzite member mainly consists of quartzites, with minor interbedded slates. The quartzites contain a few clasts of sericitised plagioclase, microcline, muscovite, biotite and rare rock fragments that contain pre-depositional fabrics. Boundaries of quartz grains are sutured. Detritial microcline was observed in the meta-arenites and quartzites of the formation. In addition to authigenic chlorites, detritial chlorites were detected as diagenetically altered or transformed from detritial biotites. Rarely, chlorite–mica stacks (CMS) were determined in slates and meta-sandstones. Partly preserved clastic textures such as micro-lamination are characteristic features for the meta-siltstones and slates of the Hüdai Formation. In general, discrete crenulation cleavage developed in sandstones/slates. Pressure solutions and fine-grained sericite are formed in the slates and silty shales (Fig. 5f).

### 4.5. Çaltepe Formation

This formation comprises recrystallized dolomite, sparitic limestone and nodular limestones, converted to calcareous slates with chlorite and sericite neo-formations. Primary textures were mostly obliterated because of recrystallization processes in dolomites, whereas micritic/biomicritic texture in the limestones was better preserved. Calcareous slates (deformed nodular limestones) in the upper part of the formation have a poorly developed slaty cleavage ($S_2$) along which chlorite and lesser fine-grained sericite is formed.

### 4.6. Seydisehir Formation

Common lithologies of the formation are slates, siltstones and sandstones. Slates and meta-siltstones have poorly developed slaty cleavages. Detritial biotites were partially chloritized in some chlorite–mica stacks (CMS). In addition to detritial chlorites, authigenic or metamorphic chlorites are also found in the pores of the matrix. The amount of CMS increases with increasing amount of detritial biotites. CMS are cut by cleavage planes that developed perpendicular to their long axes and thus they show evidence of shortening. Long axes of CMS are generally parallel to bedding, but perpendicular to poorly-developed cleavage planes.

### 4.7. Jurassic cover

Basal conglomerates of the Liassic Ilyasli Formation include quartz, feldspar and fragments of metamorphic rocks (meta-rhyolites, meta-quartz porphyries, meta-diabase rocks, slates/phyllites, meta-mudstones and quartzites) within a partly sericitized clay matrix and upper parts of the formation is composed of brownish-reddish sandstone (phyllarenite-arkose) and siltstone including high amounts of hematite. Arkosic sandstones of the formation contain zoned plagioclase of volcanogenic origin. The carbonate rocks of the overlying Liassic–Malm Derealani formation have micritic texture and include fossils and intraclastic allochems.

## 5. X-ray mineralogy

### 5.1. Bulk and phyllosilicate mineral assemblages

Neoproterozoic to Lower Paleozoic rocks in the study area contain phyllosilicates, quartz, feldspar, calcite and dolomite (Fig. 6). The abundance of calcite is higher in the Güvercinoluk and Derealani formations, whereas dolomite abundance is higher in the Çaltepe Formation. Quartz and feldspar show nearly uniform distribution from the Seydisehir to Güvercinoluk Formations. Feldspar abundance is higher in the KCPS and in meta-diabase dykes.

Phyllosilicate minerals are represented by illite, chlorite, mixed-layered chlorite–vermiculite (C–V), chlorite–smectite (C–S) and smectite. Among the phyllosilicate minerals illite, C–V and C–S are commonly found in all units, whereas chlorite is mostly detected in the Gögebakan and Seydisehir formations. The amounts of C–V and C–S slightly increase in the Güvercinoluk Formation. The KCPS is represented by an illite±C–V paragenesis. Two major phyllosilicate zones are distinguished on the basis of clay mineral associations (Fig. 6): illite+C–V+C–S±chlorite (Güvercinoluk Formation and lower parts of the Gögebakan Formation) and illite+chlorite±C–V±C–S (middle–upper parts of the Gögebakan Formation and Seydisehir Formation). The abundance of chlorite, C–V and C–S slightly increases from the Güvercinoluk Formation to the Seydisehir Formation. These minerals are mainly indicative of a volcanogenic source (Inoue et al., 1984; Inoue and Utada, 1991). The abundance of these minerals together with the increasing amount of chloritized biotites or CMS in the Seydisehir Formation indicates the majority of volcanogenic detritial material during this period. The clay fraction of the Jurassic formations contains the illite+chlorite±C–V assemblage.

### 5.2. Illite crystallinity (KI)

The KI data of the Late Neoproterozoic–Lower Paleozoic units (Table 1 and Fig. 6) show values from high-grade anchizone to epizone, whereas the values for the Jurassic cover units as Ilyasli and Derealani formations are within the late diagenetic zone. KI values in Neoproterozoic basement and Paleozoic cover units display a narrow interval changing from 0.16–0.26 KI ($\Delta°2\theta$). Jurassic formations have distinctly higher KI values between 0.28–0.49 $\Delta°2\theta$ than the underlying formations, showing a drastic drop between the Lower Paleozoic units and Jurassic units (Fig. 6).

### 5.3. $d_{(060)}$ or $b_0$ values of illites/muscovites

The $d_{(060)}$ and $b_0$ Å values of muscovite yield octahedral Mg+Fe contents and pressure conditions, respectively (e.g., Hunziker et al., 1986; Guidotti and Sassi, 1986). The $d_{(060)}$ or $b_0$ values of illites/muscovites decrease from lower to upper parts of the stratigraphic sequence investigated (Table 2 and Fig. 7). The Güvercinoluk, KCPS, Hüdai and Çaltepe formations have higher $d_{(060)}$ or $b_0$ values than the other units. High $d_{(060)}$ values of the Hüdai Formation are related to the presence of $1M$ celadonitic mica, whereas those of Güvercinoluk, KCPS and Çaltepe formations to the $2M_1$ phengitic mica. The only appearance of $1M$ celadonitic mica in the Hüdai Formation may be evaluated as a detritial input with magmatic (probably volcanic) origin (Merriman and Roberts, 1985), as found in the eastern Taurus (Bozkaya et al., 2002). But considering the existence of detritial microcline in the Hüdai Formation samples, the origin of $1M$ polytypes could be derived from plutonic rather than volcanic rocks. This also suggests that the lower boundary of Hüdai Formation represents an erosional unconformity surface (Göncüoglu, 1997; Göncüoglu and Kozlu, 2000). Higher $b_0$ values in the Çaltepe Formation compared to the overlying Seydisehir Formation and lower than Hüdai Formation (relatively low $b_0$ values but the presence of $1M$ celadonitic mica) on the other hand, may be interpreted as mineralogical evidence for an important difference in the source regions rather than higher pressure conditions, as previously indicated for the eastern Taurus Belt (Bozkaya et al., 2002; Bozkaya and Yalcin, 2004).

The Gögebakan Formation has more muscovite–phengite, whereas the Seydisehir, Ilyasli and Derealani formations have muscovite composition (Fig. 7). The phengitic components in illites/muscovites decrease from the lower to the upper parts of the succession. On the other hand, a rise in Mg+Fe content in the illites together with metamorphic grade results in lower $I_{(002)}/I_{(001)}$ ratios (e.g., Esquevin, 1969). There is a clear trend of the $I_{(002)}/I_{(001)}$ ratio of illite/muscovites towards higher values with decreasing $b_0$ values. The obtained wide range of $b_0$ values (9.004–9.040 Å) between lower and upper part of Gögebakan Formation are taken into consideration. The $b_0$ values of lower part of the succession vary between 9.022–9.040 Å which might be related to the bulk composition of the unit. The lower part of the formation is mainly made up of quartzo-feldspatic rocks and has more detritial materials of Neoproterozoic SBC (mainly K-feldspar bearing rock fragments). The mafic rocks as spilitic lavas/diabase dykes observed in the lower/middle part of the succession and more detritial materials of basement rocks in quartzo-feldspatic layers of the formation might conceivably

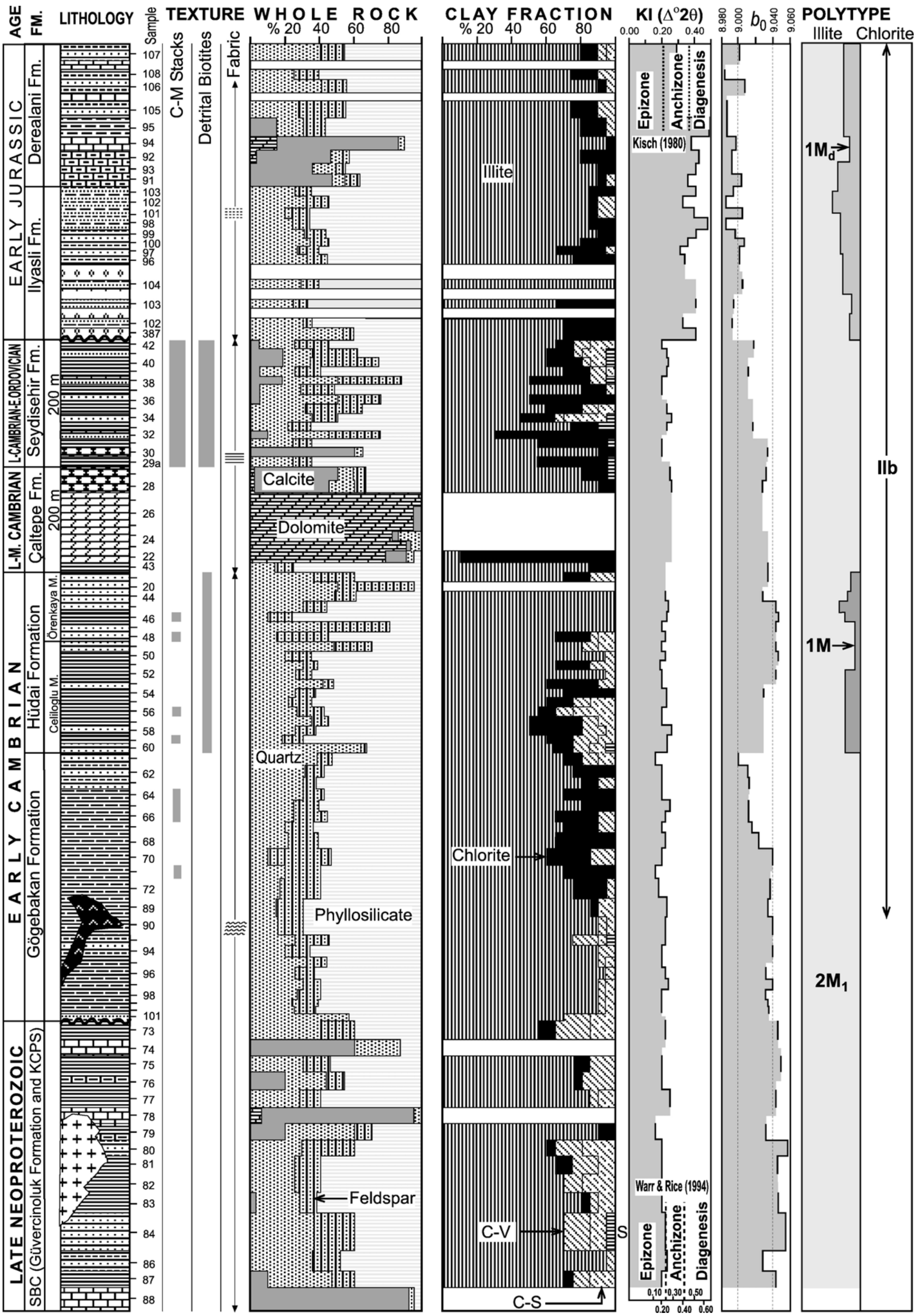


Fig. 6. Vertical distribution of mineralogic data of the Late Neoproterozoic to Early Jurassic units in the Sandıklı area.

Table 1
KI values of illites/white K-micas of Late Neoproterozoic–Jurassic rocks in the Sandıklı area

| Unit | Age | KI (Δ°2θ) | | | Diagenetic–metamorphic grade |
|---|---|---|---|---|---|
| | | Range* | Mean* | $n$ | |
| Derealani Formation (Early Jurassic Cover) | Early Jurassic (Liassic–Malm) | 0.28–0.49<br>*0.32–0.65* | 0.37<br>*0.46* | 8 | Late diagenesis |
| Ilyasli Formation (Early Jurassic Cover) | Early Jurassic (Liassic) | 0.31–0.48<br>*0.37–0.63* | 0.39<br>*0.49* | 11 | Late diagenesis |
| Seydişehir Formation (Early Paleozoic Cover) | Early Ordovician–Late Cambrian | 0.20–0.26<br>*0.19–0.29* | 0.22<br>*0.22* | 11 | Higher part of anchimetamorphism–Epimetamorphism |
| Çaltepe Formation (Early Paleozoic Cover) | Middle–Late Cambrian | 0.25–0.32<br>*0.27–0.38* | 0.27<br>*0.31* | 3 | Higher part of anchimetamorphism |
| Hüdai Formation (Early Paleozoic Cover) | Early Cambrian | 0.19–0.26<br>*0.18–0.29* | 0.22<br>*0.22* | 18 | Higher part of anchimetamorphism–Epimetamorphism |
| Gögebakan Formation (Early Paleozoic Cover) | Early Cambrian | 0.16–0.25<br>*0.14–0.27* | 0.22<br>*0.22* | 22 | Higher part of anchimetamorphism–Epimetamorphism |
| Kestel Cayı Porphyroid Suite (SBC) | Late Neoproterozoic | 0.18–0.24<br>*0.16–0.26* | 0.21<br>*0.21* | 9 | Epimetamorphism |
| Güvercinoluk Formation (SBC) | Late Neoproterozoic | 0.16–0.25<br>*0.14–0.28* | 0.20<br>*0.20* | 12 | Epimetamorphism |

*Straight and italic numbers represent the recalculated values with respect to polished slate standards (Kisch, 1980) and CIS (Warr and Rice, 1994), respectively. $n$ = Number of samples.

account for higher $b_0$ values. The bulk composition of upper part of the formation mainly consists of more aluminous clayey materials as meta-mudstone/meta-siltstone and aluminous rich layers in the upper part of the formation might account for lower $b_0$ values (9.004–9.022 Å). The marked differences of $b_0$ values in the Gögebakan Formation might be controlled by the difference of bulk composition.

The cumulative frequency distribution of $b_0$ values in muscovite of Mesozoic to Pre-Cambrian units is shown in Fig. 8. The $b_0$ values from the Neoproterozoic Güvercinoluk Formation and KCPS units are characteristic of the medium pressure facies series (Sassi and Scolari, 1974; Guidotti and Sassi, 1986), close to the boundary with the high-pressure series (Fig. 8). The change in $b_0$ values of lower part of the Early Cambrian Gögebakan Formation compared to the Neoproterozoic basement is rather weak but Gögebakan Formation still indicates conditions of typical intermediate-pressure series on $b_0$ versus $I_{(002)}/I_{(001)}$ diagram (Fig. 8). A cumulative curve of illite $b_0$ cell dimension data of the Jurassic cover units as Ilyasli and Derealani formations is consistent with low-pressure series as for Bosost (low-P/T type metamorphic belt). Low $b_0$ values of diagenetic illites are related to authigenic white mica in the matrix rather than detritial inheritance (as shown in the petrographic investigation); therefore they may reflect growth during burial (Padan et al., 1982).

### 5.4. Illite/muscovite and chlorite polytypes

The illite/muscovite polytypes in the Jurassic to Late Paleozoic covers and Neoproterozoic units show combinations of $2M_1$, $2M_1+1M_d$ and $2M_1+1M$. $1M$ and $1M_d$ polytypes are restricted to the Hüdai and Ilyasli–Derealani formations, respectively (see Fig. 6). $1M$ and $2M_1$ polytypes are respectively characteristic for celadonitic–phengitic and muscovitic dioctahedral micas (Bailey, 1984). The presence of $1M$ polytype in the Hüdai Formation indicates the existence of celadonitic/phengitic micas with high $b_0$ values. The amounts of $1M$ mica increase in slates in comparison with the meta-siltstones and meta-sandstones of the Hüdai Formation. $1M_d \rightarrow 2M_1$ conversion is completed in anchimetamorphic grade, whereas $1M$ polytypes were still preserved in epimetamorphic grade.

Table 2
$d_{(060)}$ or $b_0$ cell dimension and octahedral (Mg+Fe) contents of illite/white K-micas of Late Neoproterozoic–Jurassic units in the Sandıklı area

| Unit | Age | $b_0$ cell dimension (Å) | | Mean $d_{(060)}$ (Å) | $n$ | Octahedral Fe+Mg |
|---|---|---|---|---|---|---|
| | | Range | Mean | | | |
| Derealani Formation (Early Jurassic Cover) | Early Jurassic (Liassic–Malm) | 8.984–9.008 | 8.996 | 1.4993 | 8 | 0.28 |
| Ilyasli Formation (Early Jurassic Cover) | Early Jurassic (Liassic) | 8.985–9.008 | 8.997 | 1.4995 | 12 | 0.29 |
| Seydişehir Formation (Early Paleozoic Cover) | Early Ordovician–Late Cambrian | 9.011–9.034 | 9.020 | 1.5033 | 4 | 0.46 |
| Çaltepe Formation (Early Paleozoic Cover) | Middle–Late Cambrian | 9.028–9.035 | 9.032 | 1.5053 | 3 | 0.58 |
| Hüdai Formation (Early Paleozoic Cover) | Early Cambrian | 9.028–9.046* | 9.040* | 1.5067* | 9 | 0.65* |
| Gögebakan Formation (Early Paleozoic Cover) | Early Cambrian | 9.004–9.040 | 9.026 | 1.5043 | 14 | 0.53 |
| Kestel Çayı Porphyroid Suite (SBC) | Late Neoproterozoic | 9.029–9.055 | 9.042 | 1.5070 | 9 | 0.66 |
| Güvercinoluk Formation(SBC) | Late Neoproterozoic | 9.028–9.058 | 9.043 | 1.5072 | 9 | 0.67 |

*Measured values represent the $2M_1+1M$ polytype illites/muscovites, $n$ = Number of samples.

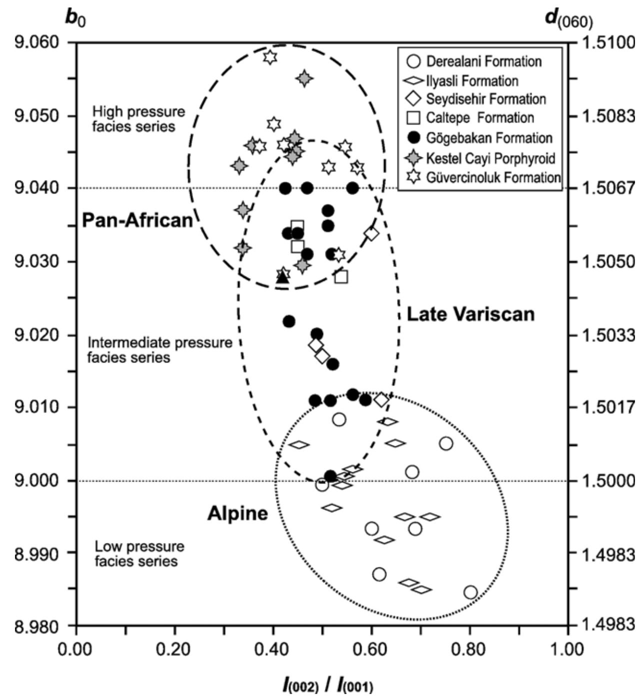


Fig. 7. $b_0$ or $d_{(060)}$ versus $I_{(002)}/I_{(001)}$ diagram of the illite/white K-micas of Late Neoproterozoic–Early Jurassic units in the Sandıklı area.

According to our studies on 15 chlorite-rich samples, only II*b* polytypes are observed in the Late Paleozoic and Jurassic cover units (see Fig. 6).

## 6. Discussion and conclusions

### *6.1. Mineralogical and textural fingerprints for Cadomian event in the Sandıklı area*

Three lines of evidence, the field observations, mineralogical and textural evidence suggest that the unconformities between the Neoproterozoic SBC and its Lower Cambrian cover (Gögebakan Formation) as well as between the Late Cambrian/Early Ordovician Seydisehir Formation and its Mesozoic cover coincide with tectonic events. As the stratigraphic gap from Ordovician to Early Jurassic is too wide to ascribe pressure differences to just one of the numerous geological events in this time-span (Göncüoglu et al., 1997) we focus the discussion on the differences across the Neoproterozoic–Cambrian boundary.

The phyllosilicate crystal-chemical data of meta-pelites and the index mineral paragenesis of the meta-basic rocks clearly indicate that both the Late Neoproterozoic and Upper Ordovician units in the Sandıklı area of the Taurides were affected by very low-grade metamorphism, especially when only KI values are considered. The KI values of Late Neoproterozoic to Late Ordovician units have similar high anchizonal to epizonal grades (Fig. 6) and suggest temperatures of ~300 °C (Frey, 1986, 1987). This temperature estimate is also in accordance with the dynamic crystallization of quartz, observed in both units. The similar KI values of both units suggest that very low-grade metamorphism was developed in post-Ordovician time and related to a single tectonic event. However the potential multiphase character of this event can be only evaluated by detailed mineralogical considerations.

In spite of the similar KI values, Late Neoproterozoic and Paleozoic units have different $b_0$ values of illites/muscovites. The Late Neoproterozoic Güvercinoluk Formation and KCPS show relatively high $b_0$ values with respect to the Early Cambrian Gögebakan Formation with high to moderate $b_0$ values (see Figs. 7 and 8). The $b_0$ lattice dimensions for illite/mica from Güvercinoluk Formation and KCPS are consistent with relatively high amounts of phengite substitution and are within the field established by Guidotti and Sassi (1986) for the higher part of the intermediate-pressure facies series (Fig. 8). The similar $b_0$ values of Güvercinoluk Formation (mean 9.043 Å) and KCPS (mean 9.042 Å) may be interpreted as either simultaneous deposition of sedimentary and volcanogenic components or similar diagenetic/metamorphic evolution at the same pressure conditions. Approximate burial pressures can be derived from $P$–$T$–$b_0$ grid of Guidotti and Sassi (1986) by extending the $b_0$ curves into sub-greenschist facies $P$–$T$ space (see Rice et al., 1989; Underwood et al., 1993). Assuming a temperature of ~300 °C (detailed in Frey, 1986, 1987) and average $b_0$ value of 9.043 Å, a pressure of ~4.2 kb can be derived, which indicates a burial depth of ~15 km. Despite of the wide range of $b_0$ values (9.004–9.040 Å) in Early Cambrian Gögebakan Formation, resulted from the bulk composition effect with similar KI values, the lower average $b_0$ data around 9.026 Å for the formation might be indicative for lower pressure conditions corresponding to ~3.2 kb, which indicates a burial depth of ~10 km (Fig. 9). These data, together with the field observations, striking differences in the type, number of foliation and deformational features between the Neoproterozoic basement and the Early Cambrian Gögebakan Formation

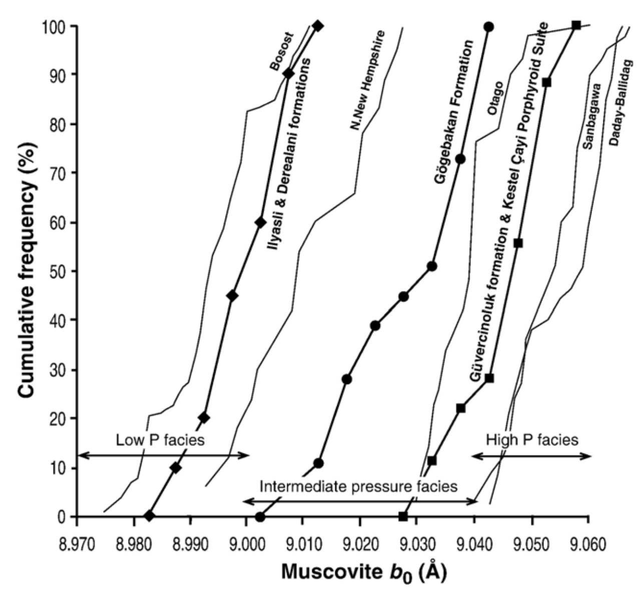


Fig. 8. Cumulative frequency versus $b_0$ plot of illite/white K-micas of Late Neoproterozoic to Early Jurassic units in Sandıklı area (other regional metamorphic terrains are taken from Sassi and Scolari, 1974; Bosost: low pressure, high temperature; Northern New Hempshire: low pressure, intermediate temperature; Otago: Barrovian type metamorphism, Sanbagawa: high pressure intermediate series).

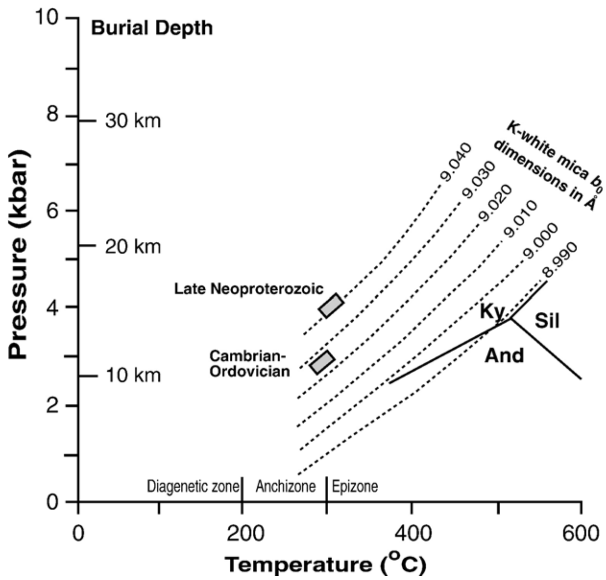


Fig. 9. *P–T* diagram showing the metamorphic conditions and corresponding burial depths of the SBC rocks and the overlying Early Cambrian cover units.

as well as the presence of angular metamorphosed pebbles displaying penetrative cleavage ($S_1$) of the SBC within the basal conglomerates of Gögebakan Formation (see Fig. 5d) are indicative for a tectonothermal event at the Neoproterozoic basement–Paleozoic cover interface.

This event can be bracketed between 543±7 Ma (the youngest zircon $^{207}Pb/^{206}Pb$ ages obtained from meta-quartz porphyry rocks of KCPS, Kröner and Şengör, 1990) or 541.3±10.9 Ma (from meta-rhyolites of KCPS, Gürsu and Göncüoglu, in press) and Early Cambrian/Tommotian (534 Ma; minimum age of trace fossils from transition levels of Gögebakan and Hüdai formations found by Erdogan et al., 2004). This data coincides with the Cadomian metamorphism in several peri-Gondwanan terranes (e.g., von Raumer et al., 2002). We interpret that within this time span the SBC was deformed and metamorphosed, uplifted and eroded prior to the deposition of the Early Cambrian red clastics of the Gögebakan Formation.

### 6.2. Regional distribution of the Cadomian event in western Anatolia and surroundings

In the Tauride Belt, Late Neoproterozoic ages were mainly reported from metamorphic massifs with high-grade Alpine metamorphic overprint (e.g., Menderes Massif, Dora et al., 2001; Bitlis Massif, Göncüoglu and Turhan, 1983) or from the Istanbul–Zonguldak terrane in NW Turkey (see Fig. 1).

The tectonothermal evolution of the Menderes Massif is controversial. Şengör et al. (1984) and Satir and Friedrichsen (1986) had suggested that late Pan-African granitoid intrusions occurred. However, based on the cross-cutting contact relations with the host rocks, these blastomylonitic granitoids (augen gneisses) were considered as Tertiary intrusions by Bozkurt and Oberhansli (2001) and Erdogan and Güngör (2004). Recent zircon $^{207}Pb/^{206}Pb$ and U/Pb ages suggest that this igneous event ranges from 570 to 540 Ma (Hetzel and Reischmann, 1996; Loos and Reischmann, 1999) or from 566 to 541 Ma (Gessner et al., 2004). Even though the Cadomian intrusion age of these granitoids is now generally accepted, the deformation and metamorphism of them is still attributed to the Alpine (Oligocene) "Main Menderes Metamorphism (MMM; Şengör et al., 1984)". The granitoids are similar with the mylonitic quartz-porphyry rocks of the KCPS in their crystallization ages and geochemical fingerprints (Gürsu and Göncüoglu, 2001; Gürsu et al., 2004; Gürsu and Göncüoglu, in press). It is univocally accepted since Ketin (1966) that both Menderes and Sandıklı inlayers of the Taurides were parts of the same continental crust and shared to be in the same tectonic setting throughout their history (e.g., Göncüoglu et al., 1997).

Based on structural, petrographical and geochemical data obtained by our studies in the Sandıklı area, the following alternative interpretations are provided:

(i) Sandıklı and Menderes were at different paleo-tectonic settings in respect to northern Gondwana during the Late Neoproterozoic and were affected by dissimilar Neoproterozoic geological events. An analogous model was suggested by Kröner and Şengör (1990), who located the Sandıklı magmatism to the southern margin of Angara craton of Siberia and suggest that the Pan-African evolution in the Middle East may have been terminated by the collision of Angara with Gondwana in the Early Cambrian. However, Kozlu and Göncüoglu (1997) have shown that this model cannot be applied to Sandıklı nor to the Menderes, as they include the same rock-units and succession of events that can be correlated all along the peri-Gondwanan terranes during this time span.

(ii) Sandıklı and Menderes were at similar paleotectonic settings within the northern margin of Gondwana and include the same post-collisional magmatism during the Late Neoproterozoic, but the ongoing post-collisional extension with the development of strike-slip faults resulted in their separation. The Sandıklı-type basement with its continuation in central and eastern Taurides, with well-developed mylonitic metamorphism, represents such a mega shear zone. This model may help to explain the development of Early Cambrian trans-tensional basins on the Tauride–Anatolide platform previously suggested by Kozlu and Göncüoglu (1997) and Göncüoglu (1997).

(iii) The preservation of the mineralogical signatures of the Late Neoproterozoic–Early Cambrian event in the Sandıklı area is due to the inadequate Alpine overprint compared with the MMM which attained amphibolite facies conditions (e.g., Candan and Dora, 1998). This interpretation would imply that Menderes and Sandıklı-type tectonic units were at different structural levels during the alpine crustal thickening/post-collisional extension, both of which could be responsible for the Alpine metamorphism. In this case, the Menderes tectonic unit was probably in a lower structural level than Sandıklı and the Alpine metamorphism has completely erased the fingerprints of earlier tectonothermal events. This model seems to be an acceptable working hypotheses, as a

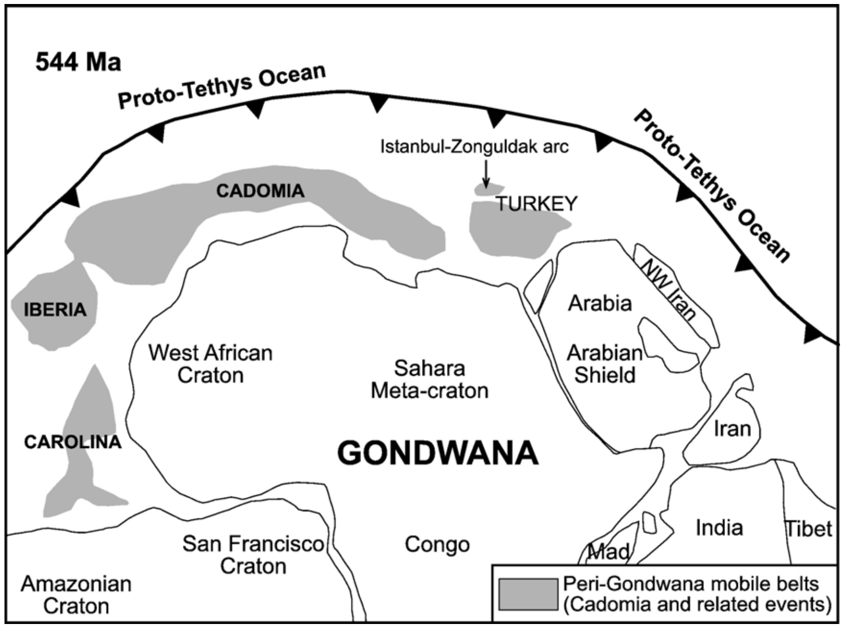


Fig. 10. Schematic reconstruction of Late Neoproterozoic paleogeography and the location of Anatolia (modified after Unrug, 1997 and Kusky et al., 2003).

number of thermal events (for a brief review see Bozkaya et al., 2002) deciphered in the less metamorphosed units of the Taurides including the late Variscan-time events (Göncüoglu et al., 2003) in the central Taurides have not been recorded (or yet identified) in the Menderes Massif.

To conclude, field, structural and mineralogical data obtained from the Sandıklı area of the Taurides, the basement complex including siliciclastic rocks and post-collisional I-type granitoids is affected by regional dynamo-metamorphism. This event coincides with the Cadomian metamorphism recorded in the basement rocks of an extensive zone from Iberia (Ossa Morena zone, Bandres et al., 2002) to southeast Europe (e.g., Bulgaria; Haydoutov and Yanev, 1997). This zone is characterized by the presence of terranes, all derived from Gondwana, but disrupted by subsequent Variscan and Alpine tectonics (e.g., Murphy et al., 2002). It is suggested that the Taurides and the Istanbul–Zonguldak terrane in northwest Anatolia were located at a similar paleogeographic position but further in the East (Fig. 10). For a more detailed localization of the Gondwana-derived Turkish terranes paleomagnetic studies are needed.

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## References

Bailey, S.W., 1984. Classification and structures of the micas. In: Bailey, S.W. (Ed.), Micas. Mineralogical Society of America, Reviews in Mineralogy, vol. 13, pp. 1–12.

Bailey, S.W., 1988. X-ray diffraction identification of the polytypes of mica, serpentine and chlorite. Clays and Clay Minerals 36, 193–213.

Bandres, A., Eguiluz, L., Ibarguchi, J.I., Palacios, T., 2002. Geodynamic evolution of a Cadomian arc region: the northern Ossa–Morena zone, Iberian massif. Tectonophysics 352, 105–120.

Bertrand, L., 1921. Les Anciennes Mers de la France et leur Depots. Flammarion, Paris.

Bevins, R.E., Robinson, D., 1988. Short paper: low grade metamorphism of the Welsh Basin Lower Paleozoic succession: an example of diastathermal metamorphism. Journal of the Geological Society of London 145, 363–366.

Bozkaya, Ö., Yalcin, H., 2004. Diagenetic to low-grade metamorphic evolution of clay mineral assemblages in Paleozoic to early Mesozoic rocks of the Eastern Taurides, Turkey. Clay Minerals 39, 481–500.

Bozkaya, Ö., Yalcin, H., Göncüoglu, M.C., 2002. Mineralogic and organic responses to stratigraphic irregularities: an example from the Lower Paleozoic very low-grade metamorphic units of the Eastern Taurus Autochthon, Turkey. Schweizerische Mineralogische und Petrographische Mitteilungen 82, 355–373.

Bozkurt, E., Oberhansli, R., 2001. Menderes massif (western Turkey): structural, magmatic and metamorphic evolution. International Journal of Earth Sciences 89, 697–708.

Brime, C., Garcia-Lopez, S., Bastida, F., Valin, M.L., Sanz-Lopez, J., Aller, J., 2001. Transition from diagenesis to metamorphism near the front of the Variscan regional metamorphism (Cantabrian Zone, Northwestern Spain). Journal of Geology 109, 363–379.

Brindley, G.W., 1980. Quantitative X-ray mineral analysis of clays. In: Brindley, G.W., Brown, G. (Eds.), Crystal Structures of Clay Minerals and their X-ray Identifications. Mineralogical Society of London, pp. 411–438.

Candan, O., Dora, O.Ö., 1998. Granulite, eclogite and blueschist relicts in the Menderes Massif: an approach Pan-African and Tertiary metamorphic evolution. Geological Bulletin of Turkey 41, 1–35 (in Turkish with English abstract).

Candan, O., Dora, O.Ö., Oberhansli, R., Cetinkaplan, M., Partzsch, J.H., Warkus, F.C., Dürr, S., 2001. Pan-African high-pressure metamorphism in the Precambrian basement of the Menderes Massif, western Anatolia, Turkey. International Journal of Earth Sciences 89, 793–811.

Dean, W.T., Özgül, N., 1994. Cambrian rocks and faunas, Hüdai area, Taurus Mountains, southwestern Turkey. Bulletin del'Institut Royal Des Scienes Naturelles de Belgique Sciences de la Terra 64, 5–20.

D'Lemos, R.S., Strachan, R.A., Topley, C.G. (Eds.), 1990. The Cadomian orogeny. Geological Society of London Special Publication, vol. 51, p. 423.

Dora, O.Ö., Candan, O., Kaya, O., Koralay, E., Dürr, S., 2001. Revision of "leptite-gneiss" in the Menderes Massif: a supracrustal meta-sedimentary origin. International Journal of Earth Sciences 89, 832–847.

Erdogan, B., Güngör, T., 2004. The problem of the core–core boundary of the Menderes Massif and an emplacement mechanism for regionally extensive gneissic granites, Western Anatolia (Turkey). Turkish Journal of Earth Sciences 13, 15–36.

Erdogan, B., Uchman, A., Güngör, T., Özgül, N., 2004. Lithostratigraphy of the lower Cambrian metaclastics and their age based on trace fossils in the Sandıklı region, southwestern Turkey. Geobios 37, 346–360.

Esquevin, J., 1969. Influence de la composition chimique des illites sur leur cristallinité. Bulletin-Centre de Recherches Pau-SNPA 3, 147–153.

Frey, M., 1986. Very low-grade metamorphism of the Alps—an introduction. Schweizerische Mineralogische und Petrographische Mitteilungen 66, 13–27.

Frey, M., 1987. Very low-grade metamorphism of clastic sedimentary rocks. In: Frey, M. (Ed.), Low Temperature Metamorphism. Blackie, Glasgow and London, pp. 9–58.

Frey, M., Teichmüller, M., Teichmüller, R., Mullis, J., Künzi, B., Breitschmid, A., Gruner, U., Schwizer, B., 1980. Very low-grade metamorphism in external parts of the Central Alps: illite crystallinity, coal rank and fluid inclusion data. Eclogae Geologicae Helvetiae 73, 173–203.

Gessner, K., Collins, A.S., Ring, U., Güngör, T., 2004. Structural and thermal history of poly-orogenic basement: U–Pb geochronology of granitoid rocks in the southern Menderes massif, Western Turkey. Journal of Geological Society of London 161, 93–101.

Göncüoglu, M.C., 1997. Distribution of Lower Paleozoic rocks in the Alpine terranes of Turkey: paleogeographic constraints. In: Göncüoglu, M.C., Derman, A.S. (Eds.), Early Paleozoic Evolution in NW Gondwana. Turkish Association of Petroleum Geologists Special Publications, Turkey, pp. 13–23.

Göncüoglu, M.C., Kozlu, H., 2000. Early Palaeozoic evolution of the NW Gondwanaland: data from southern Turkey and surrounding regions. Gondwana Research 3, 315–323.

Göncüoglu, M.C., Turhan, N., 1983. New results on the age of Bitlis metamorphics. Mineral Research Exploration Bulletin 95/96, 1–5.

Göncüoglu, M.C., Dirik, K., Kozlu, H., 1997. General characteristics of pre-Alpine and Alpine terranes in Turkey: explanatory notes to the terrane map of Turkey. Annales Geologiques des Pays Helleniques 37, 515–536.

Göncüoglu, M.C., Turhan, N., Göncüoglu, Y., 2001. Vestiges of Late Paleozoic ("Variscan") events within the Tauride–Anatolide Belt, Turkey: implications for the Paleotethyan evolution in NW Peri-Gondwana. ESF Europrobe Meeting, Ankara, pp. 24–26.

Göncüoglu, M.C., Turhan, N., Tekin, K., 2003. Evidence for the Triassic rifting and opening of the Neotethyan Izmir–Ankara Ocean, northern edge of the Tauride–Anatolide Platform, Turkey. Bulletin of the Geological Society of Italy, Special 2, 203–212.

Grathoff, G.H., Moore, D.M., 1996. Illite polytype quantification using wildfire calculated X-ray diffraction patterns. Clays and Clay Minerals 44, 835–842.

Guidotti, C.V., Sassi, F.P., 1986. Classification and correlation of metamorphic facies series by means of muscovite $b_0$ data from low-grade metapelites. Neues Jahrbuch fur Mineralogie. Abhandlungen 153, 363–380.

Gürsu, S., 2002. Geology and petrogenesis of pre-Paleozoic magmatic rocks in the inner western Anatolia (SW Afyon) region. Ph.D. thesis, Hacettepe University (in Turkish with English abstract).

Gürsu, S., Göncüoglu, M.C., 2001. Characteristic features of the Late Precambrian felsic magmatism in western Anatolia: implications for the Pan-African evolution in NW Peri-Gondwana. Gondwana Research 4, 169–170.

Gürsu, S., Göncüoglu, M.C., 2005. Early Cambrian back-arc volcanism in the western Taurides, Turkey: implication for rifting along the northern Gondwanan margin. Geological Magazine 142, 617–631.

Gürsu, S., Göncüoglu, M.C., in press. Petrogenesis and tectonic setting of Cadomian felsic igneous rocks, Sandıklı area of the western Taurides, Turkey. International Journal of Earth Science.

Gürsu, S., Göncüoglu, M.C., Bayhan, H., 2004. Geology and geochemistry of the pre-Early Cambrian rocks in the Sandıklı area: implications for the Pan-African evolution in NW Gondwanaland. Gondwana Research 7, 923–935.

Haydoutov, I., 1989. Precambrian ophiolites, Cambrian island arc and Variscan suture in South Carpathian–Balkan region. Geology 17, 905–908.

Haydoutov, I., Yanev, S., 1997. The Protomoesian microcontinent of the Balkan Peninsula — a peri-Gondwanaland piece. Tectonophysics 272, 303–313.

Hesse, R., Dalton, E., 1991. Diagenetic and low-grade metamorphic terranes of Gaspé Peninsula related to the geological structure of the Taconian and Acadian orogenic belts, Quebec Appalachians. Journal of Metamorphic Geology 9, 775–790.

Hetzel, R., Reischmann, T., 1996. Intrusion age of Pan-African augen-gneisses in the southern Menderes Massif and the age of cooling after Alpine ductile extensional deformation. Geological Magazine 133, 565–572.

Hunziker, J.C., Frey, M., Clauer, N., Dallmeyer, R.D., Fredrichsen, H., Flehmig, W., Hochstrasser, K., Roggviler, P., Schwander, H., 1986. The evolution of illite to muscovite: mineralogical and isotopic data from the Glarus Alps, Switzerland. Contributions to Mineralogy and Petrology 92, 157–180.

Inoue, A., Utada, M., 1991. Smectite-to-chlorite transformation in thermally metamorphosed volcanoclastic rocks in the Kamikita area, Northern Honshu, Japan. American Mineralogist 76, 628–640.

Inoue, A., Utada, M., Nagata, H., Watanabe, T., 1984. Conversion of triochahedral smectite to interstratified chlorite–smectite in Pliocene acidic pyroclastic sediments of the Ohyu District, Akita Prefecture, Japan. Clay Science 6, 103–116.

Ketin, İ., 1966. Cambrian formations of SE Anatolia and their correlation with the Cambrian of E Iran. Mineral Research and Exploration Institute of Turkey, Bulletin 66, 75–87 (in Turkish with English abstract).

Kisch, H.J., 1980. Illite crystallinity and coal rank associated with lowest-grade metamorphism of the Taveyanne greywacke in the Helvetic zone of the Swiss Alps. Eclogae Geologicae Helvetiae 73, 753–777.

Kisch, H.J., 1990. Calibration of the anchizone: a critical comparison of illite "crystallinity" scales used for definition. Journal of Metamorphic Geology 8, 31–46.

Kisch, H.J., 1991. Illite crystallinity: recommendations on sample preparation, X-ray diffraction settings, and interlaboratory samples. Journal of Metamorphic Geology 9, 665–670.

Kozlu, H., Göncüoglu, M.C., 1997. Stratigraphy of the Infracambrian rock-units in the Eastern Taurides and their correlation with similar units in Southern Turkey. In: Göncüoglu, M.C., Derman, A.S. (Eds.), Early Paleozoic Evolution in NW Gondwana. Turkish Association of Petroleum Geologists Special Publications, Turkey, pp. 50–61.

Kröner, A., Şengör, A.M.C., 1990. Archean and Proterozoic ancestry in late Precambrian to early Paleozoic crustal elements of southern Turkey as revealed by single-zircon dating. Geology 18, 1186–1190.

Kusky, T.M., Abdelsalam, M., Tucker, R.D., Robert, J., Stern, R.J., 2003. Evolution of the east African and related orogens and the assembly of Gondwana. Precambrian Research 123, 81–85.

Kübler, B., 1968. Evaluation quantitative du métamorphisme par la cristallinité de l'illite. Bulletin-Centre de Recherches Pau-SNPA 2, 385–397.

Loos, S., Reischmann, T., 1999. The evolution of the southern Menderes Massif in SW Turkey as revealed by zircon dating. Journal of the Geological Society of London 156, 1021–1030.

Merriman, R.J., Frey, M., 1999. Patterns of very low-grade metamorphism in metapelitic rocks. In: Frey, M., Robinson, D. (Eds.), Low Grade Metamorphism. Blackwell Science, Oxford, pp. 61–107.

Merriman, R.J., Roberts, B., 1985. A survey of white mica crystallinity and polytypes in pelitic rocks of Snowdonia and Llyn, Nort Wales. Mineralogical Magazine 49, 305–319.

Moore, D.M., Reynolds, R.C., 1997. X-ray Diffraction and the Identification and Analysis of clay Minerals. Oxford University Press, New York.

Murphy, J.B., Nance, R.D., 1989. Model for the evolution of Cadomian–Avalonian belt. Geology 17, 735–738.

Murphy, J.B., Eguiluz, L., Zulauf, G., 2002. Cadomian orogens, peri-Gondwanan correlatives and Laurentia–Baltica connections. Tectonophysics 352, 1–9.

Neubauer, F., 2002. Evolution of late Neoproterozoic to early Paleozoic tectonic elements in central and southeast European mountain belts: review and syntheses. Tectonophysics 352, 87–103.

Offler, R., Miller, J.M.C.L., Gray, D.R., Foster, D.A., Bale, R., 1998. Crystallinity and $b_0$ spacing of K-white micas in a Paleozoic accretionary complex, Eastern Australia: metamorphism, paleogeotherms, and structural style of an underplated sequence. Journal of Geology 106, 495–509.

Öngür, T., 1973. Batı Toroslar, Isparta büklümü kuzey kenarı cevresinde jeolojik gelisme. In: Bingöl, E. (Ed.), Geological Congress for the 50th Anniversary of the Turkish Republic Proceedings, Ankara, pp. 95–102 (in Turkish with English abstract).

Özgül, N., 1976. Some geological aspects of the Taurus orogenic belt (Turkey). Bulletin of the Geological Society of Turkey 19, 65–78 (in Turkish with English abstract).

Özgül, N., Bölükbasi, S., Alkan, H., Öztas, Y., Korucu, M., 1991. Tectonostratigraphic units of the Lake District, Western Taurides, Tectonics and hydrocarbon potential of Anatolia and surrounding regions. In: Turgut, S. (Ed.), Ozan Sungurlu Symposium Proceedings, Ankara, pp. 213–237.

Padan, A., Kisch, H.J., Shagam, R., 1982. Use of the lattice parameter $b_0$ of dioctahedral illite/muscovite for the characterization of P/T gradients of incipient metamorphism. Contributions to Mineralogy and Petrology 79, 85–95.

Rahn, M., Mullis, J., Erdelbrock, K., Frey, M., 1995. Alpine metamorphism in the North Helvetic flysch of the Glarus Alps, Switzerland. Eclogae Geologicae Helvetiae 88, 157–178.

Rice, A.H.N., Bevins, R.E., Robinson, D., Roberts, D., 1989. Thrust-related metamorphic inversion in the Caledonides of Finnmark, north Norway. In: Daly, J.S., Cliff, R.A., Yardley, B.W. (Eds.), Evolution of Metamorphic Belts. Special Publication of Geological Society, vol 43, pp. 413–421.

Roberts, B., Merriman, R.J., Pratt, W., 1991. The influence of strain, lithology and stratigraphical depth on white mica (illite) crystallinity in mudrocks from the vicinity of the Corris Slate Belt, Wales: Implications for the timing of metamorphism in the Welsh Basin. Geological Magazine 128, 633–645.

Sarmiento, G.N., Göncüoglu, M.C., Fernandez-Remolar, D., Garcia-Lopez, S., 1997. Small shelly fossils from the Çaltepe Formation (late Lower Cambrian–early Middle Cambrian) in its type locality, western Taurides (Turkey). In: Grandal D'anglades, A., Guitérrez Marco, J.C., Santos Fidalgo, L. (Eds.), Paleozoico Inferior del Noroeste de Gondwana. Sociedade Espanola Paleontologia, pp. 113–115.

Sassi, F.P., Scolari, A., 1974. The $b_0$ value of the potassic white micas as a barometric indicator in low grade metamorphism of pelitic schists. Contributions to Mineralogy and Petrology 45, 143–152.

Satir, M., Friedrichsen, H., 1986. The origin and evolution of the Menderes massif, W Turkey: a rubidium/stronium and oxygen isotope study. Geologische Rundschau 75, 703–714.

Şengör, A.M.C., Yilmaz, Y., 1981. Tethyan evolution of Turkey: a plate tectonic approach. Tectonophysics 75, 181–241.

Şengör, A.M.C., Satir, M., Akkök, R., 1984. Timing of tectonic events in the Menderes Massif, western Turkey: implications for tectonic evolution and evidence for Pan African Basement in Turkey. Tectonics 3, 693–707.

Underwood, M.B., Laughland, M.M., Kang, S.M., 1993. A comparison among organic and inorganic indicators of diagenesis and low-temperature metamorphism, Tertiary Shimanto Belt, Japan. Geological Society of America Special Publication 273, 45–61.

Unrug, R., 1997. Rodinia to Gondwana: the geodynamic map of Gondwana supercontinent assembly. GSA Today 7, 1–5.

Vidal, G., Palacios, G., Gaez-Vintaned, J.A., Diez-Balda, M.A., Grant, S.V.F., 1994. Neoproterozoic and early Cambrian geology and Paleontology of Iberia. Geological Magazine 131, 729–765.

von Raumer, J.F., Stampfli, G.M., Borel, G., Bussy, F., 2002. Organization of pre-Variscan basement areas at the north-Gondwanan margin. International Journal of Earth Sciences 91, 35–52.

Warr, L.N., Rice, A.H.N., 1994. Interlaboratory standardization and calibration of clay mineral crystallinity and crystallite size data. Journal of Metamorphic Geology 12, 141–152.

Warr, L.N., Primmer, T.J., Robinson, D., 1991. Variscan very low-grade metamorphism in southwest England: a diastathermal and thrust-related origin. Journal of Metamorphic Geology 9, 751–764.

Yang, C., Hesse, R., 1991. Clay minerals as indicators of diagenetic and anchimetamorphic grade in an overthrust belt, external domain of southern Canadian Appalachians. Clay Minerals 26, 211–231.